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Carbon Sequestration Using Exotic Larches in Central Maine

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Abstract: The carbon sequestration potential of exotics might be considered as one of the several alternatives for forest adaptation to climate change. The results presented here demonstrate that exotic larches' (*Larix* spp.) growth rates for both carbon accumulation and traditional forest products exceed those of both natural regeneration and other planted species when planted on a good site in Maine. Recent re-measurement of a species-site trial established in 1988 represents the 34th growing season. Species included Black Spruce (BS) (*Picea mariana* Mill.), European larch (EL) (*Larix decidua* Mill.), hybrid larch (HL) (*L. x marschelensi*), Japanese larch (JL) (*L. kaempferi* (Lam.) Carrière), Jack pine (JP) (*Pinus banksiana* Lamb.), Red pine (RP) (*Pinus resinosa* Ait.), Tamarack (TL) (*L. larcinia* (Du Roi) K. Koch), and White spruce (WS)(*Picea glauca* (Moench) Voss). All three of the exotic larches outgrew the other species. Hybrid larch had over nearly twice the merchantable volume (m^3 ha^{-1}) and over three times the sawlog volume (green tonnes ha^{-1}) than Red pine. Hybrid larch had the highest growth rate at age 34, over 20 m^3 per hectare per year (nearly 3.3 cords ac^{-1} $year^{-1}$ or 6.8 $tons^{-1}$ $acre^{-1}$ $year^{-1}$). The other two exotic larches are growing at over 19 m^3 ha^{-1} $year^{-1}$ (3 cords $acre^{-1}$ $year^{-1}$ or 6.4 tons $acre^{-1}$ $year^{-1}$). Converting these growth rates to accumulation of CO_2eq over the 34-year period produces stunning contrasts compared to native species. Over the 34-year period, larch hybrids sequestered 2.4 times as much CO_2eq as the untreated plots (444 vs. 186 $tonnes^{-1}$ ha^{-1}). We discuss practical implications for forest management and carbon policies.

Keywords: carbon sequestration; carbon; exotic larch; hybrid larch; European larch; Japanese larch; tamarack; *Larix x marschelensi*; *Larix decidua*; *Larix kaempferi*; *Larix laricina*

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1. Introduction

Global forests are the only large carbon sink that humanity has in its grasp to mitigate carbon accumulation in the atmosphere. Forest management is a well-understood mechanism for providing humanity's needs for fiber, fuel, and food. Forest carbon sequestration results are available from several management schemes ranging from reserves to managing high stocking while maintaining production [1]. One potential scheme is planting exotic species that exceed indigenous species in their ability to sequester carbon.

Foresters, biologists, and horticulturists have planted exotic species to understand their characteristics and potential uses. Espinoza and Gonzalez [2] identified five benefits for using exotic species:

1. Where indigenous species do not provide the type, quantity, or quality of forest products.
2. Generally, exotic species have higher growth rates than native species.
3. Exotic species used in forestry plantations can grow in poor sites with better yield than indigenous species.
4. Exotic species can usually adapt to different environmental conditions.
5. Exotic species could be used as a source of different types of products and so reduce the pressure on native species.

Perhaps the most famous use of exotic tree species is the Monterey Pine (*Pinus radiata* D. Don) in New Zealand. Numerous other studies have shown how exotic tree species can provide greater wood fiber productivity compared to local tree species [3–5]. Miller [6] found that poplar (*Populus* spp.) hybrids grown under intensive forest management exceeded natural regeneration stands in producing fiber for biomass and may be effective for rapidly sequestering carbon. Ciccarese et al. [7] suggested that short-rotation plantations offer a double-positive input by providing feed-stocks for bioenergy to displace fossil fuel use while storing carbon in biomass and soil. In this paper, we explore the use of exotics to increase carbon sequestration rapidly. This research strengthens arguments made elsewhere [8].

This paper reports on the results of a 1988 species-site trial established to determine the growth, value, and use of conifer plantations in central Maine. A key purpose of planting these plantations was to offset a predicted shortfall in fiber production following losses due to a widespread insect infestation, eastern spruce budworm (*Choristoneura fumiferana*). Otherwise, plantation establishment in Maine has had a limited and spotty history, because most native species naturally regenerate well. This trial was not established to examine carbon sequestration; however, we have re-evaluated the data to identify tree growth and carbon accumulation patterns that we use to draw significant conclusions about how these exotics accumulate carbon. We primarily address biomass carbon accumulation and have not evaluated soil carbon or carbon in down and dead trees. We know of no other such trial anywhere in the northeast with such a range of species, replication, duration, and history of repeated re-measurement. The area has had no management activity since the initial planting.

2. Materials and Methods

This study was part of a larger randomized complete block design on three previously forested sites to determine growth and development of planted conifers over a range of site qualities. (Location of sites on shown in Figure 1, named for the township in which they reside; Lily Bay (LB), Chase Stream (CS), Brighton Plantation (BP).) The Chase Stream Study reported here was one of three sites selected by Carl Haag on Scott Paper Company land in 1988 to determine the relationship between planted tree species response and site quality [9]. The other two sites (Brighton Plantation (BP) and Lily Bay (LB)) have since been harvested and are no longer available for study. This site was fully measured at ages 5, 10, 16, partially measured at age 20, fully measured at age 27 and again fully measured in 2021 at age 34.

The Chase Stream site is located on a north-facing slope at an elevation of about 380 m (1250 feet). The soils are of the Telos-Chesuncook-Elliotsville Association and are well- and moderately-well drained to a maximum depth of 100 cm (43 inches). The site was likely clearcut in 1985 or 1986 and treated with glyphosate or glyphosate-sulfmeturon mixture in 1987 to reduce competition with native broad-leaved tree species and other vegetation (for more information on site quality, see Gilmore et al. [10]).

At Chase Stream, a total of 49 blocks at 16.5 m (54 feet) by 16.5 m (54 feet) (0.0669421 acres or 0.027 hectares) were laid out. Of these, 39 were planted. It is presumed that the remaining 10 were not planted due to surface rocks. Eight species were planted with different seed sources and stock types. Species included were European larch, Japanese larch, Tamarack, Hybrid larch, White and Black spruce, Jack and Red pine. With different seed sources and planting stock, there were 13 different combinations. These were planted in 3 replications, making 39 planted plots (see Maass [9] for further details).

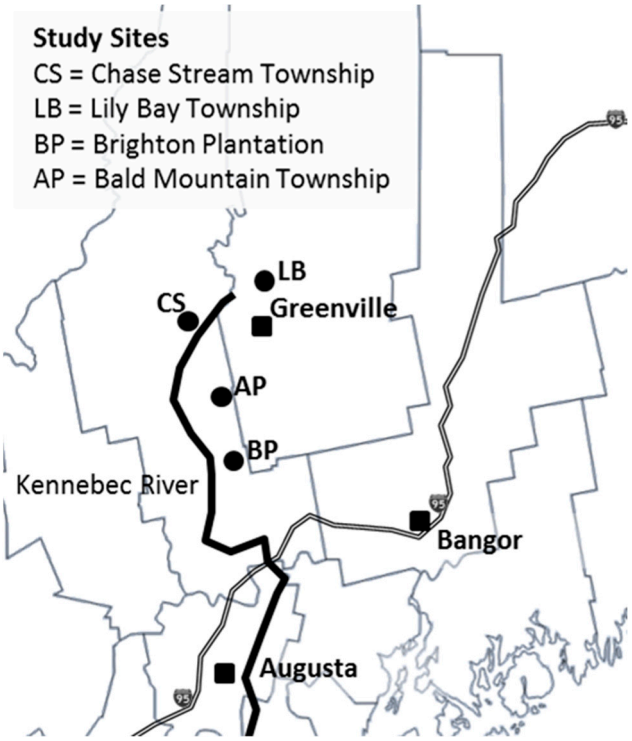


Figure 1. Study sites in central Maine, USA. Maine counties are shown along with the cities of Augusta and Bangor along Interstate 95. The three sites were designated as Chase Stream (CS on the map), Lily Bay (LB on the map), and Brighton Plantation (BP on the map). A comparison site described later is Austin Pond (AP on the map).

The planted plots had six rows of 6 trees or 36 total trees in each plot. The outside row of trees on all sides was considered to be a border. The inner test block consisted of four rows of 4 trees or 16 trees. At 2.7 m (9 feet) by 2.7 m (9 feet) spacing, the plot size was 0.012 hectares (0.02975 acres). It is these test blocks that we report on in this paper.

In 2021, 34 growing seasons after planting, we identified each planted tree by block and tree number. Because of our interest in carbon sequestration by exotics, all living and standing dead planted trees were tallied. We tallied trees forked below breast height as separate trees. We measured diameter to breast height (dbh) to the nearest 0.1 inches (0.25 cm) using a diameter tape. Height was measured using Haglof and Suunto Clinometers to the nearest 0.03 m (0.1 feet). Suunto Clinometers were used when the Haglof Clinometers were not functioning.

In growth and yield studies similar to this, non-planted control blocks are typically not examined or included in the analysis. On other sites planted next to exotic larches, we observed that the adjacent naturally regenerated sites were inferior in growth of desirable species. For this study, to quantify what was apparent, we measured trees in three unplanted blocks. In the "outblocks", all trees at least 4 inches (10.2 cm) dbh or larger were recorded within the 16.5 m (54 feet) by 16.5 m (54 feet) blocks. These outblocks cannot be strictly considered control blocks. However, the data gathered from them provide insight. No accommodation was made for the shadow effect from adjacent plots.

All volumes were calculated using Kozak taper equations following a macro developed by Li et al. [11]. Merchantable volume was measured above a 0.15 m (6 inch) stump to a 9 cm (3 inch) top diameter. Sawlog volume and weight were calculated for trees 9.0 inches (23 cm) dbh and larger to a 12.7 cm (5 inch) top. Topwood was calculated between the 12.7 cm (5 inch) and 9 cm (3 inch) top. Pulpwood was calculated for trees with diameters less than 23 cm (9 inches). For related methods, see Gilmore et al. [12].

Survival, height, diameter, and volumes for each species were compared using MS Excel one-way ANOVAs using an alpha of 0.01 ($\alpha = 0.01$).

$MTCO_2eq$ estimation: A MS Excel spreadsheet using diameter distribution was used to generate estimates of green tons of carbon $acre^{-1}$ for the eight species sampled (see Appendix B). This spreadsheet used the composite formulas estimating green tons of carbon $acre^{-1}$ that were derived for 6 species groups [13]. The green tons estimate was then recalculated to produce $MTCO_2eq\ ha^{-1}$ estimates (multiplying green tons $acre^{-1}$ times 2.47 hectares $acre^{-1}$ times 0.91 Mtonnes ton^{-1} times 44 mass of CO_2eq 12 mass of $carbon^{-1}$). Assignments to groups were as follows: the four larch species (European, Hybrid, Japanese, and Tamarack) to the Cedar/Larch group, Jack and Red pine to the Pine group, and Black and White spruce to the Spruce/Fir group. We calculated average tree component estimates for the following pieces: stem wood, bark, bole (arithmetic sum of stem wood and bark), foliage, tops and branches, total aboveground (arithmetic sum of bole, foliage, and tops and branches), coarse roots, and total above and below ground (arithmetic sum of total aboveground and coarse roots).

3. Results

Survival: Percent survival of the original 16 test plot trees in each block (forks not included) is shown in Figure 2. Survival through age 27 of 80% or higher for all species was considered acceptable for further analysis. At age 27, there was no significant difference in survival between the species ($\alpha = 0.01$). Only in the last measurement did we see a decline in the spruces. At age 34, only Black spruce had a significantly lower survival ($\alpha = 0.01$) than the other species.

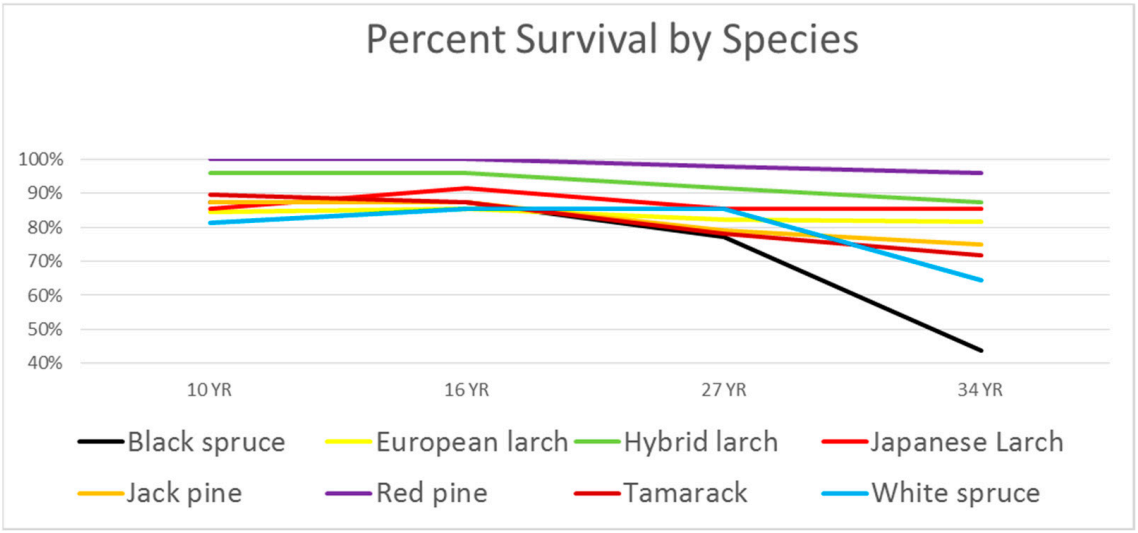


Figure 2. Percent survival of single test plot trees.

Table 1 shows the number of dead trees between ages 27 and 34. Only Japanese larch experienced no mortality between these two measurements. Black spruce and White spruce show a downturn at age 34. We believe that this is due to overtopping of these species by adjacent taller trees. One of the three black spruce blocks is surrounded on four sides by exotic larch, and 10 of its 16 test plot trees died between ages 27 and 34. An average of 3 out of 16 White spruce trees died, as well.

Table 1. Number of dead trees between ages 27 and 34 in the test plots.

Species	Tree Mortality
Black spruce	17
European larch	1
Hybrid larch	2
Japanese larch	
Jack pine	4
Red pine	1
Tamarack	8
White spruce	9

The number of forked trees differed by species, with Tamarack and White spruce having the most (Table 2). It is not clear what the reason is for the forked trees, perhaps animal predation or a late spring frost. By tallying the volume of the fork trees in the last measurement, some additional volume was added compared to the previous measurements.

Table 2. Number of forked trees tallied in the 2021 measurement for the first time within the test blocks.

Species	Tree Mortality
Black spruce	2
European larch	2
Hybrid larch	
Japanese larch	2
Jack pine	2
Red pine	
Tamarack	9
White spruce	5

Volume-related Tree Attributes: The three exotics had the tallest (and statistically very similar) average height (Figure 3 and Table 3). The exotics differed in QMD, but were not statistically different. Tamarack and Red pine were not statistically different in either height or QMD. Tamarack surpassed the spruces in both height and QMD at age 34 and was significantly taller and larger. Black and white spruce showed the lowest height and QMD increment. Interestingly, the average height and QMD for the outblocks were higher than either of the spruces, but not statistically different. In the spruce blocks, the planted trees were of low vigor, poor survival, and virtually all were overtopped by the surrounding blocks.

Table 3. Mean Height (m) and QMD (cm) and groupings by significance (α = 0.01).

Summary	Average ht (m)	Groupings by Significance (α = 0.01)	Average QMD (cm)	Groupings by Significance (α = 0.01)
Hybrid larch	24.6	a	23.9	a
European larch	24.0	a	24.7	a
Japanese larch	24.5	a	23.5	a
Tamarack	18.7	b	18.8	b
Red pine	18.1	b	21.0	b
Jack pine	16.9	c	17.2	b,c
White spruce	12.6	c	14.0	c
Black spruce	11.9	c	14.1	c
Outblocks	13.3	c	15.7	c

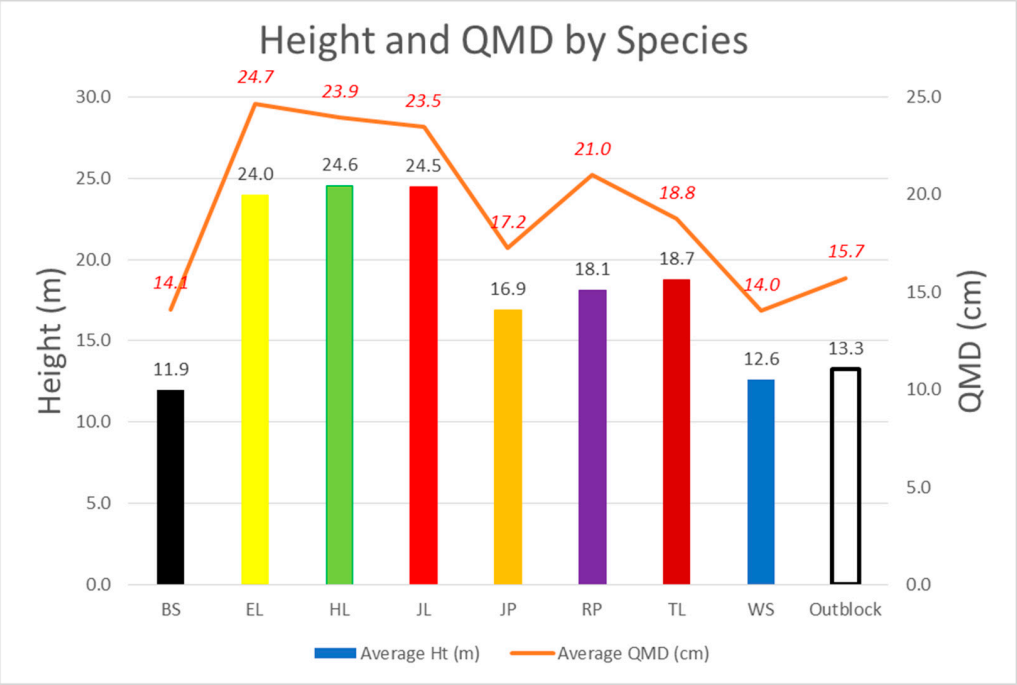


Figure 3. 34-year average height and quadratic mean diameter (QMD). Bars and black data labels indicate height and the orange line with red italicized numbers indicates QMD for each species.

Volume calculations (green tons ha^{-1}) are based on both height and diameter measurements. The three exotic larches, particularly the hybrid larch, performed much better than the other species (Figure 4 and Table 4). The hybrid larch had more than twice the volume of Red pine, while European larch had 75% and Japanese larch had 65% more volume than Red pine. Remarkably, the naturally regenerated outblocks had more merchantable volume than either of the spruces.

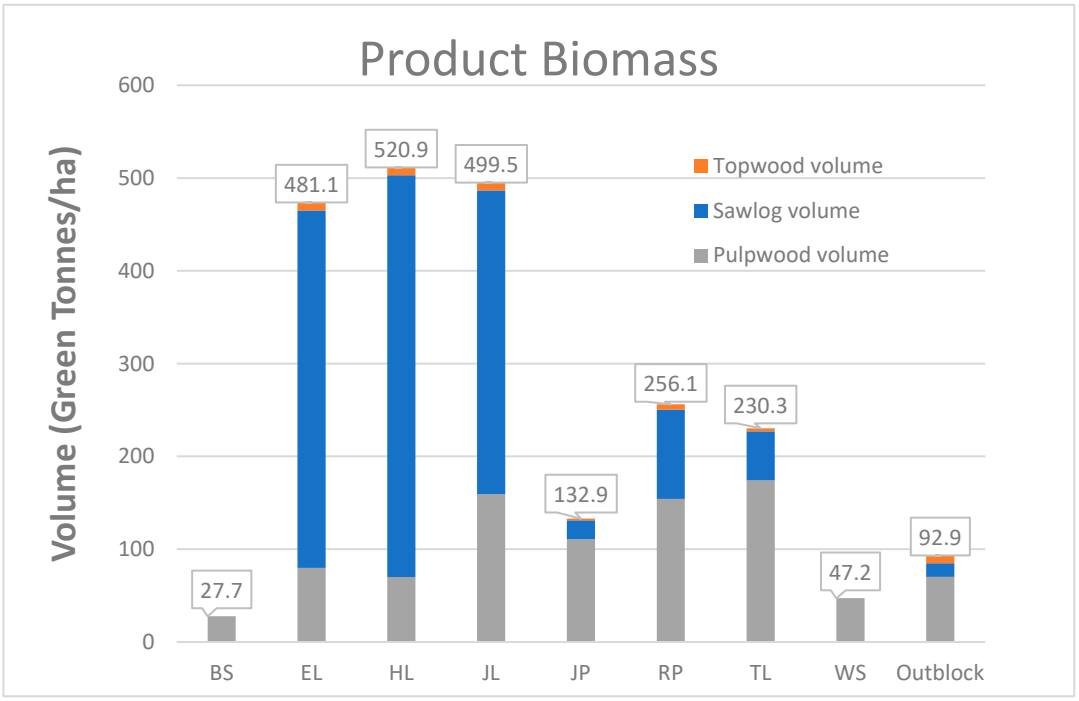


Figure 4. Merchantable green tonnes per hectare of weight by product class.

Table 4. List of species by Merchantable green tonnes per hectare.

Species	Green Tonnes ha^{-1}	Grouping by Significance (α = 0.01)
Hybrid larch	520.9	a
Japanese larch	499.5	a
European larch	481.1	a
Red pine	256.1	b
Tamarack	230.3	b
Jack pine	132.9	c
Outblocks	92.9	c
White spruce	47.2	d
Black spruce	27.7	d

Statistically, there were four groups (Table 4). The means of three exotics were not different from one another (Table 4) and all were significantly greater than the other species. The means of Tamarack and Red pine were next and not significantly different. The means of Jack pine and the outblocks were significantly different from and greater than the spruces.

Examining green tons per hectare by product classes, the exotic larches have most of the weight in sawlog size classes (Figure 4). Among Red pine and Tamarack, green weight is roughly 50/50 sawlogs and pulp. For Jack pine, the spruces, and the outblocks, the preponderance of the weight was in pulpwood. As noted in Table 1, there was no mortality in Japanese larch, and dead trees were not tallied in the outblocks.

Mean Annual Increment Trends: Mean Annual Increment trends for all the species over time are indicative of future growth trends (Figure 5). As we expected, the hybrid larch is growing the best and appears to be continuing to grow quite well. The other two exotic larch species follow similar growth trends. Red pine is growing the best of the non-exotics and is successful at 11.2 m^{-3} ha^{-1} year $^{-1}$ (1.9 cords ac^{-1} year^{-1}). Remarkably, tamarack continues to grow well and may not have reached its full potential at age 34. However, this is due in part to the inclusion of forked trees at the last measurement. The two spruces are last and appear to be declining in growth at this measurement, which is expected as they are suppressed by overtopping adjacent plots and are experiencing substantial mortality.

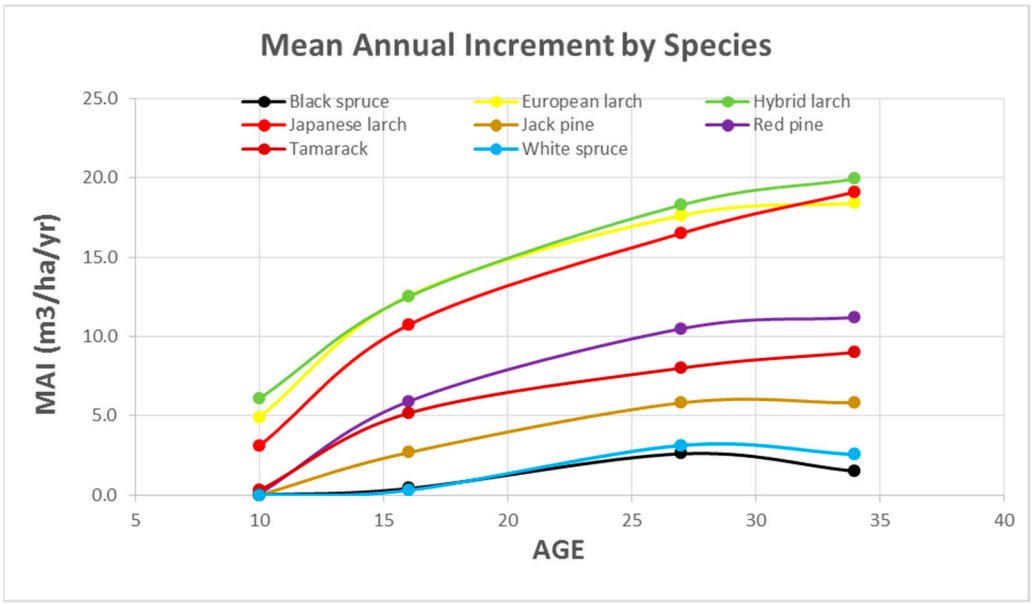


Figure 5. Mean Annual Increment of planted species.

In the naturally regenerated outblocks, balsam fir (*Abies balsamea* (L.) Mill.), white birch (*Betula papyrifera* Marsh.), quaking aspen (*Populus tremuloides* Michx.), and red maple

(*Acer rubrum* L.) made up the preponderance of the trees on these plots. Several balsam fir and quaking aspen grew to reach sawlog size class (23+ cm) (Figure 6).

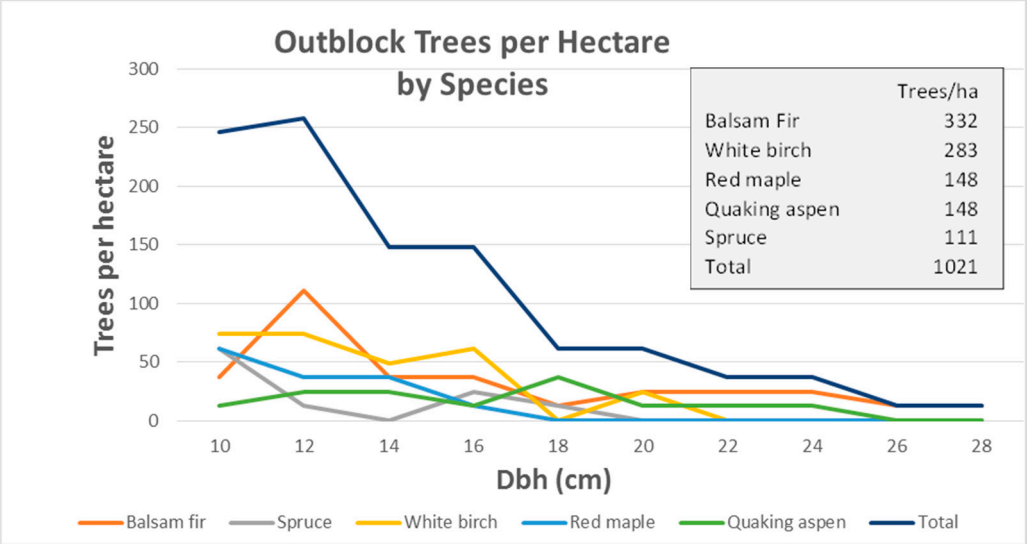


Figure 6. Outblock trees per hectare by Species and diameter at breast height (cm).

We compare stocking rates and growth as calculated by mean and periodic annual increment (MAI and PAI) (Table 5). Growth by the exotic larches and Red pine continues at high rates despite high stocking. MAI and PAI for the two spruces demonstrate that these species are in decline.

Table 5. List of basal area and incremental growth by species.

Species	BA (m^2 ha^{-1})	MAI (m^3 ha^{-1} yr^{-1})	PAI (m^3 ha^{-1} yr^{-1})
Black spruce	10.0	1.5	−0.463
European larch	52.6	18.4	3.600
Hybrid larch	52.4	19.9	4.412
Japanese larch	50.3	19.1	4.901
Jack pine	24.6	5.8	0.973
Red pine	44.1	11.2	2.340
Tamarack	29.5	9.0	2.156
White spruce	15.4	2.5	0.052

Tree Carbon Dioxide equivalence: Shown as CO_2 equivalence (Figure 7 based on statistically significant data shown in Table 4), the results show that exotic larches sequester more CO_2eq than other species, with the hybrid taking the lead at nearly 460 MTonnes of CO_2e ha^{-1} over the 34-year period. (The spreadsheet showing the calculated values is in Appendix A). Red pine accumulated 376 Mtonnes. Tamarack, the native larch, accumulated nearly 195 MTonnes. The outblocks, with measuring trees just 10.2 cm and larger at dbh, have accumulated nearly 187 Mtonnes in the 34 years since plantation establishment. By comparison, the Maine state-wide average is 204 MTonnes ha^{-1} for above and belowground tree carbon on timberland (from FIA data (USDA Forest Service [14]) calculating 25 tons $acre^{-1}$ × 2.47 acres ha^{-1} × 0.91 Mtonnes ton^{-1} × 44 mass of CO_2eq 12 mass of $carbon^{-1}$).

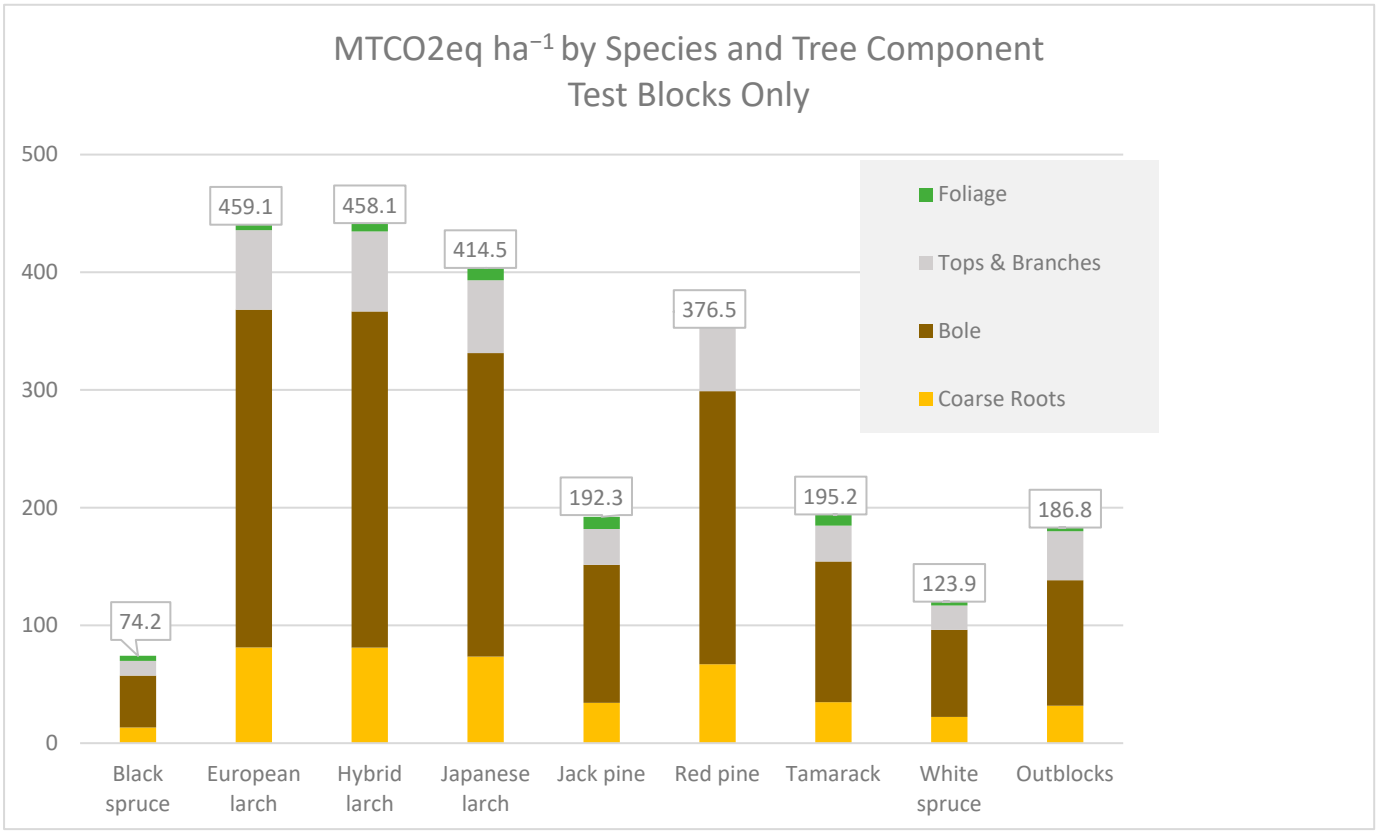


Figure 7. Above and Below Ground CO_2eq in Metric tonnes per hectare.

4. Discussion

In this trial, at age 34, exotic larches are much greater in height, diameter, and have much more volume than other planted species. Hybrid larch exceeded both European and Japanese larch, but there was no statistically significant difference between the three species. Additionally, Red pine outgrew Jack pine and the two spruce species. Non-planted blocks accumulated volume and carbon better than either of the two spruces. An unanticipated result is that the native Tamarack grew better than the spruces on this site. Landowners who are averse to planting exotics might consider this native species.

In this paper, we have documented important growth comparisons; exactly how this more rapid growth should be credited to either CO_2 reduction goals or marketing as carbon credits is a totally different and difficult subject which we do not address here.

We compare these volumes to both managed and unmanaged spruce-fir production on a nearby study area. The Austin Pond (AP on the map) (in Bald Mountain Township, ME) study was established to examine the growth and development of naturally regenerated spruce-fir stands using chemical release alone and in combination with pre-commercial thinning treatments [15] (Table 3, p. 390). Bataineh states that merchantable volume ranged from 70.6 m^3 ha^{-1} for un-thinned and untreated control to 99.7 m m^3 ha^{-1} for glyphosate-triclopyr thinned treatment after 33 years following treatment. The merchantable volume in this species-site trial ranges from 9 m^3 ha^{-1} for the black spruce to 306 m m^3 ha^{-1} for European larch and 386 m^3 ha^{-1} for the hybrid larch after 34 years. Further, a widely used synthesis report [16] (p. 49) shows northeastern regional averages for northern hardwoods of 72.8 m^3 ha^{-1} at age 35. While site differences likely account for some of the growth differences, our results clearly indicate that exotic species can potentially exceed the volume and carbon growth of native species.

Graphing the comparison of the results of this study to other studies demonstrates the greater volume (and therefore greater biomass and carbon sequestration) of the exotics in a fewer number of years (Figure 8).

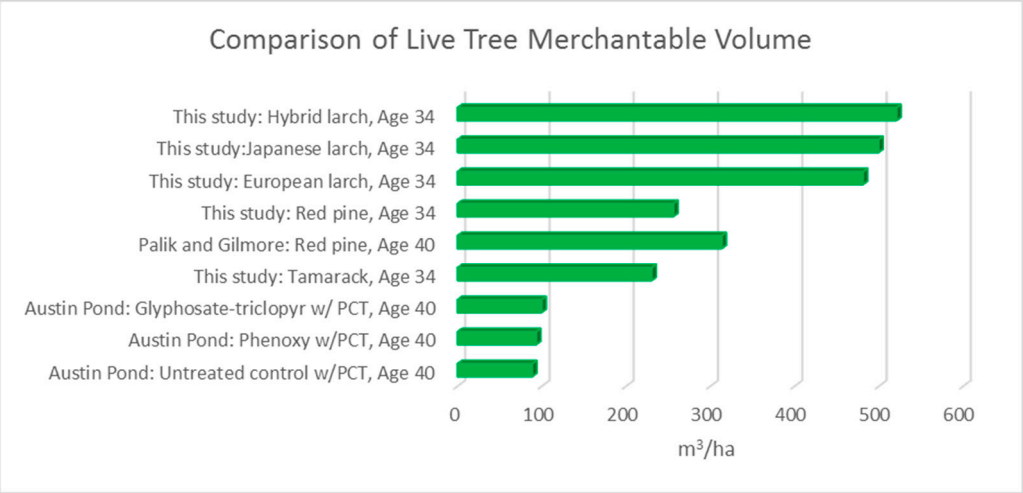


Figure 8. Comparison of merchantable volume (m^3 ha^{-1}), this study and others.

Red pine growth reported here is not quite as good as the Red pine in the Lake States region at 7.8 m^3 ha^{-1} $year^{-1}$ (44.8 cunits for site index of 75 at age 40 for 180 square feet per acre of basal area) [17] (p. 49).

The 2021 observation indicates that regeneration under the spruces and pines consisted of ferns and grasses, while under the exotic larches, sugar maple (*Acer saccharum* Marsh.) regeneration is abundant. Similarly, in the 2014 measurement, the field crew observed that the site had a preponderance of sugar maple in the understory at that time (Figures 9 and 10). Detailed analysis of the understory under the various plantation regimes needs to be done. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.



Figure 9. Understory below spruce plots largely consists of ferns. David Maass photo.



Figure 10. Understory below larch plots is largely sugar maple. David Maass photo.

We also see that these reported volumes are not unique to this particular study. We have data from over 100 different sampled stands (Figure 11), some of which come from Gilmore [18] in Maine and northern New Hampshire. Mean annual increment (MAI) can range widely from just 5 to nearly 25 m^3 ha^{-1} $year^{-1}$. The average for the exotics is over 10 m^3 ha^{-1} $year^{-1}$, however for tamarack it is under 7 m^3 ha^{-1} $year^{-1}$. Gilmore et al. [10] discussed stocking standards for European larch.

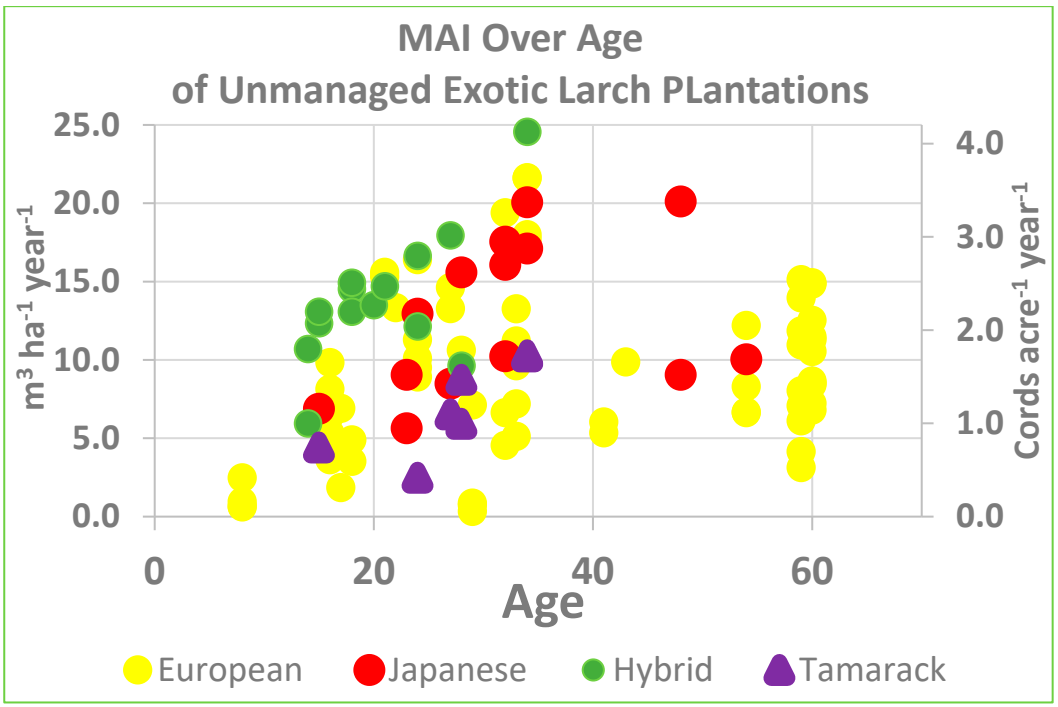


Figure 11. Mean Annual Increment (MAI) of Exotic Larch Plantations in Maine.

Other examples of growth rates of exotic larches are shown below in Appendix A (Tables A1–A3).

Exotic larches have been planted since the 1850s [19]. The oldest plantation of which we are aware is on the Marsh-Billings-Rockefeller National Historic Park in Woodstock, VT, planted in 1887. Decades of documented experience exist in New York [20,21]; Pennsyl-

vania [22]; New Hampshire [23]; Eastern Canada [24,25]; for earlier literature on eastern North America, see Hunt [26]; Genys [27]; Jeffers and Isebrands [28]; Jacobs [29]; Carter et al. [30]; Carter and Maass [31]; Gerlach [32]; for Sweden, see Eko et al. [33].

Based on what we provide here, we conclude that exotic larches provide rapid and sustained carbon sequestration superior to that of many native species. Carbon accumulation is rapid for all of the larix species, including native tamarack. At age 34, these species exceed the carbon accumulation of native naturally regenerated species. We have to ask if there is a place for these species in any state-wide carbon policy.

We suggest that plantations of these species might be used as a short-term measure until state-wide carbon goals are reached. We recognize the need for native species and habitats as a long-term goal for policy. In fact, Hua et al. [34] found that natural systems offer benefits beyond plantations. For more information on rates and drivers for monoculture plantations, see Bukoski [35].

The quickest increase in carbon sequestration is through afforestation. To that end, we examine what increases might be accomplished if non-forested sites were planted with exotic larch. The Natural Resources Inventory [36] dataset published for the United States Department of Agriculture shows 593,000 hectares (1.466 million acres) in uncultivated and other rural land categories in Maine, New Hampshire, and Vermont. Suppose it would be possible to encourage landowners to plant half of this land with exotic larches. In 35 years, that land would sequester 123 million MTonnes of CO_2eq (using 415 MTonnes CO_2eq ha^{-1} from for Japanese Larch in Figure 7). Over those 34 years, that land base could accumulate 3.62 million Mtonnes annually. According to the EPA [37], a typical passenger vehicle emits 4.6 Mtonnes of CO_2eq each year. Thus, sequestration in this land base would be equivalent to the CO_2 of 786,750 passenger vehicles each year, surpassing the number of registered passenger vehicles in the three states.

Because of rapid growth and early production of harvestable timber, the economics of planting larch are favorable, as discussed recently [38,39]. Early bud break and rapid spring-time growth is responsible for the rapid stand development [40]. Furthermore, larch species are rot-resistant and are suitable for durable wood products, unlike other fast-growing species of aspen or willow, and thus offer superior long-term carbon storage.

An important point is that virtually all of the measurements noted here are in unmanaged stands. If under management, many would have been thinned long ago. Initial work, as well as our observations in the field, suggests that thinnings and stocking level control would significantly improve value growth and stand vigor [38,41,42].

To be clear, we have not examined soil carbon or the carbon flux with dead and dying trees. These are important components of the forest carbon taken as a whole. This study was not established to address these critical components. We may be able to address these issues later.

For private landowners, exotic larch might be considered to rehabilitate or replace degraded and/or beech-dominated stands. The early thinnings possibly as soon as age 15 can provide short-term income. Later income can be derived from later thinnings and returning the degraded forest to a more productive forest with desirable shade-tolerant species of maple, oak, or spruce. We have shown in the pictures above that the exotics allow for understory sugar maple to become established.

A major concern for exotic species is the risk that they may become invasive [2,43]. Anecdotally, we have witnessed volunteer larch regeneration becoming established on exposed mineral soil and gravel pits. However, because these species are shade intolerant, there is a lower likelihood that they will survive competition. Despite their being established across the northern US and eastern Canada [38], we have encountered limited literature regarding these species becoming invasive [44]. Additionally, the native tamarack performed better than other more widely planted species at least through age 34. If exotics are a concern because they could be invasive or for other reasons, landowners could consider tamarack.

There is concern that the exotics might hybridize with the native tamarack. In a genetics trial, the researchers tried to establish a European larch–tamarack hybrid [45–47]. They found that due to the very different timing of pollination and fertilization of the two species, it was very difficult to cross with low seed set and maturation even in a greenhouse environment. This suggests that any wild cross would likely fail. There are areas of the northeast where future conifer stocking is a concern. Anywhere tall conifers confer some habitat or aesthetic advantage would have the potential for using these larches.

This work suggests that there is value in exploring a number of related topics, including potential for use in restoration of heavily cut sites, habitat values, other nontimber resource benefits and impacts, and understanding why understories in the larch plots differ so markedly from the other conifers (on this question, see Royer-Tardif et al. [48]). As widespread deployment of planted larches is imminent, there is time for exploring these and other issues.

5. Conclusions

Emerging research is now arguing that carbon sequestration is becoming more and more urgent, with early action necessary. This research shows that plantations of exotic larches can boost carbon storage within the widely used 2050 period often stated for carbon goals.

1. After clearcutting on good sites, exotic larches far outperform natural regrowth, as well as commonly planted conifers, in terms of merchantable volume as well as carbon storage over 34 years.
2. Other work shows that due to rapid growth and early availability of merchantable wood, economic results for planting these species are favorable for many landowners.
3. Larches seem to have a neutral to favorable effect in understories compared to other planted conifers.
4. Monoculture plantings are far from the only potential applications of these species.
5. Research on various potential impacts of larch plantings on soils, habitat, and other values is warranted.

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Appendix A

Table A1. Jericho Forest in Vermont, age 75.

From University of Vermont Jericho Forest
• The stand has produced an average of 200 bf ft/ac/yr over its 75-year life and a significant volume of larch remains standing. • Three dominant/codominant trees felled and left behind after the 2014 harvest have been measured: they averaged 105 feet tall and 19 inches dbh. At an age of 75 years (2014 − 1941 + 2 years old at age of planting), they thus averaged 1.4 ft in height and 0.25 in dbh growth per year.

Source: [49].

Table A2. Larch stands at Fox Forest, New Hampshire, age 62.

	Pine Glen	Per Year	No. Trees	Bible Hill	Per Year	No. Trees
Dbh cm	297	0.48	48	34.5	0.56	53
Ht m	25.9	0.42	48	31.7	0.52	5

Source: [50].

Table A3. Larch stands at Winona State Forest, New York (measured 2021).

Stand	Age	No. Plots	Ave dbh cm	Per year	Height m	Per Year
1	72	1	46.5	0.65	28.06	0.39
2	68	1	56.8	0.83	29.59	0.44
3	71	3	41.2	0.58	26.13	0.37

Source: [51].

Appendix B

$MTCO_2e$ Estimates at Age 34 by Species and Size Class, Test Blocks Only derived from Jenkins species groupings and components (GTR NE-319)

MTonnes CO2 eq ha^{-1}

Species	Size Class	Stem Wood	Stem Bark	Bole	Foliage	Tops and Branches	Total Aboveground	Coarse Roots	Total Above and Belowground
BS	Sapling	4.27	0.81	5.07	0.56	1.64	7.27	1.62	8.89
	Poletimber	32.84	6.11	38.95	3.70	10.91	53.57	11.72	65.29
	Sawtimber	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	37.11	6.92	44.02	4.26	12.55	60.84	13.34	74.17
EL	Sapling	0.93	0.18	1.11	0.12	0.36	1.59	0.35	1.94
	Poletimber	151.25	27.73	178.98	14.89	43.38	237.25	51.18	288.43
	Sawtimber	90.29	16.44	106.73	8.32	23.92	138.97	29.77	168.73
	Total	242.47	44.35	286.82	23.33	67.66	377.81	81.30	459.11
HL	Sapling	3.73	0.71	4.44	0.49	1.43	6.36	1.41	7.78
	Poletimber	170.39	31.23	201.62	16.68	48.55	266.85	57.53	324.38
	Sawtimber	67.26	12.26	79.52	6.24	17.97	103.73	22.23	125.96
	Total	241.39	44.19	285.58	23.41	67.95	376.94	81.18	458.12

JL	Sapling	0.93	0.18	1.11	0.12	0.36	1.59	0.35	1.94
	Poletimber	159.31	29.24	188.55	15.82	46.12	250.49	54.08	304.57
	Sawtimber	57.65	10.51	68.15	5.35	15.40	88.90	19.06	107.96
	Total	217.89	39.92	257.81	21.29	61.88	340.98	73.49	414.47
JP	Sapling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Poletimber	98.87	18.25	117.12	10.38	30.45	157.96	34.30	192.26
	Sawtimber	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	98.87	18.25	117.12	10.38	30.45	157.96	34.30	192.26
RP	Sapling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Poletimber	195.93	36.02	231.95	19.79	57.82	309.57	66.95	376.52
	Sawtimber	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	195.93	36.02	231.95	19.79	57.82	309.57	66.95	376.52
TL	Sapling	1.87	0.35	2.22	0.25	0.72	3.18	0.71	3.89
	Poletimber	89.51	16.50	106.01	9.27	27.15	142.43	30.88	173.31
	Sawtimber	9.60	1.75	11.36	0.89	2.57	14.81	3.18	17.99
	Total	100.98	18.60	119.58	10.40	30.43	160.42	34.77	195.19
WS	Sapling	9.60	1.81	11.41	1.26	3.69	16.36	3.64	20.00
	Poletimber	52.74	9.78	62.52	5.78	16.99	85.29	18.60	103.90
	Sawtimber	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	62.34	11.59	73.93	7.04	20.68	101.65	22.24	123.89
Outblocks	Sapling	12.57	2.81	15.38	1.18	8.24	24.80	5.15	29.95
	Poletimber	75.76	15.45	91.21	5.69	33.32	130.22	26.64	156.86
	Sawtimber	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Total	88.33	18.26	106.59	6.87	41.57	155.02	31.79	186.81

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