# Enhanced Fibre Production and Management of Lodgepole Pine

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## Acknowledgements

The development of this paper was supported by the following organizations which are members of the Foothills Growth and Yield Association: Alberta Newsprint Company, Blue Ridge Lumber, Canadian Forest Products, Millar Western Forest Products, Spray Lake Sawmills, Sundance Forest Industries, Sunpine Forest Products, Weldwood of Canada, Weyerhaeuser Company, Alberta Sustainable Resource Development, and the Foothills Model Forest.

## Abstract

Significant uncertainties confront planners and silviculturists attempting to forecast the post-harvest growth and yield of lodgepole pine. These include changes in stand structure and dynamics relative to fire-origin stands, effects and efficacy of regeneration practices, responses to density and nutrition management, and shifts in site index. Observed growth responses to harvesting and reforestation are described, and implications for forest planning, silviculture, and research are discussed.

During the last 5 years, an association of 9 Alberta timber companies, the Alberta Department of Sustainable Resource Development (ASRD), the Foothills Model Forest, and other collaborating agencies, has implemented a number of projects designed to improve the assessment of lodgepole pine growth and yield in managed stands. Work undertaken by the association and ASRD is described, with emphasis on observed trends in the dynamics and structure of managed post-harvest stands.

Knowledge gained from the Alberta studies and elsewhere suggests that regeneration practices following harvesting are capable of increasing fibre production relative to that of fire-origin stands. However, these shifts are not without associated risks and residual uncertainties. Implications of the observed trends are discussed. Priorities are identified for enhancing productivity, managing risks, and reducing uncertainties.

**Keywords**: lodgepole pine, growth and yield, forest management, silviculture.

## Introduction

This paper discusses the potential for enhanced fibre production and management of lodgepole pine, with emphasis on stands regenerated after harvesting in Alberta, Canada. A brief overview of the range, importance, and characteristics of the species is followed by a synopsis of past growth and yield research and the accumulating evidence for increased productivity in regenerated stands. Ongoing work in Alberta is summarized, with emphasis on trends in post-harvest regenerated stands. Opportunities, threats, and uncertainties regarding enhanced fibre production are reviewed, and some conclusions drawn concerning priorities for forest planning, silvicultural practice, and research.

## Range and Importance of Lodgepole Pine

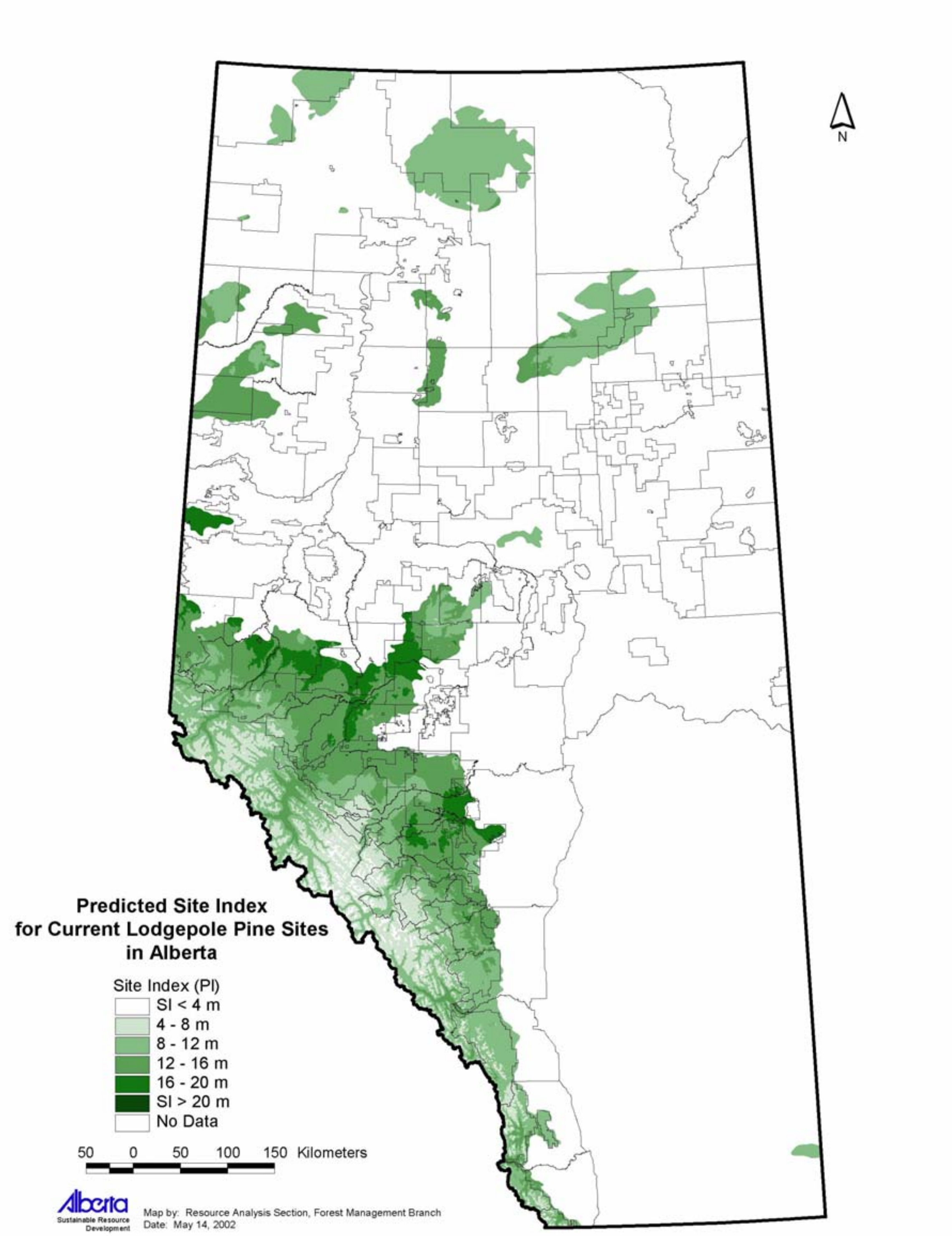
Lodgepole pine (*Pinus contorta* Doug) is the most widely distributed conifer in western North America. Western Canada and the western United States share both the potential for enhancing its fibre production, and the uncertainties associated with the productivity of stands regenerated after harvesting. Lodgepole pine is a major contributor to Alberta's forest industry, as well as providing protective cover for the vital watersheds of the eastern slopes of the Rocky Mountains. Figure 1 shows the distribution of the species in Alberta, together with predicted site index as mapped by Monserud and Huang (2002). The range indicated on the map does not include the zone of hybridization with jack pine. The highest site indices are indicated at lower elevations on the edge of the current range.

## Characteristics Relevant to Management and Enhanced Fibre Production

The species' edaphic and climatic tolerances, considerable genetic variation, and regenerative capacity are frequently remarked upon. One of its most significant characteristics over much of its range is its closed (serotinous) cone habit, permitting seed to survive major disturbances. As a result, it typically regenerates very prolifically following fire. Lodgepole pine is reproductively active at an early age; seeds are small, readily dispersed, and have minimal germination requirements; seedlings are frost hardy and drought-resistant; juvenile growth rates are rapid; and the tree is able to thrive on a broad spectrum of soil types from waterlogged organics to well-drained glacial outwashes and nearly everything in between (Wheeler and Critchfield, 1985). It is a shade-intolerant pioneer. Albertans have made the species their provincial tree.

Lodgepole pine's propensity to regenerate at very high densities following fire leads to what are variously referred to as "stagnated" or "repressed" stands, where height growth and timber production may be substantially reduced by intra-specific competition. Because repression affects all trees, including the dominants traditionally used to estimate site potential, the effects of density and site are confounded in fire-origin stands. This creates problems in forecasting the growth and yield of regenerated stands. Growth and yield studies in both the U.S. and Canada have for some time attempted to account for density effects (e.g. Alexander *et al* 1967, and more recently Huang *et al* 2001).

**Figure 1. Distribution and predicted site index of lodgepole pine in Alberta**

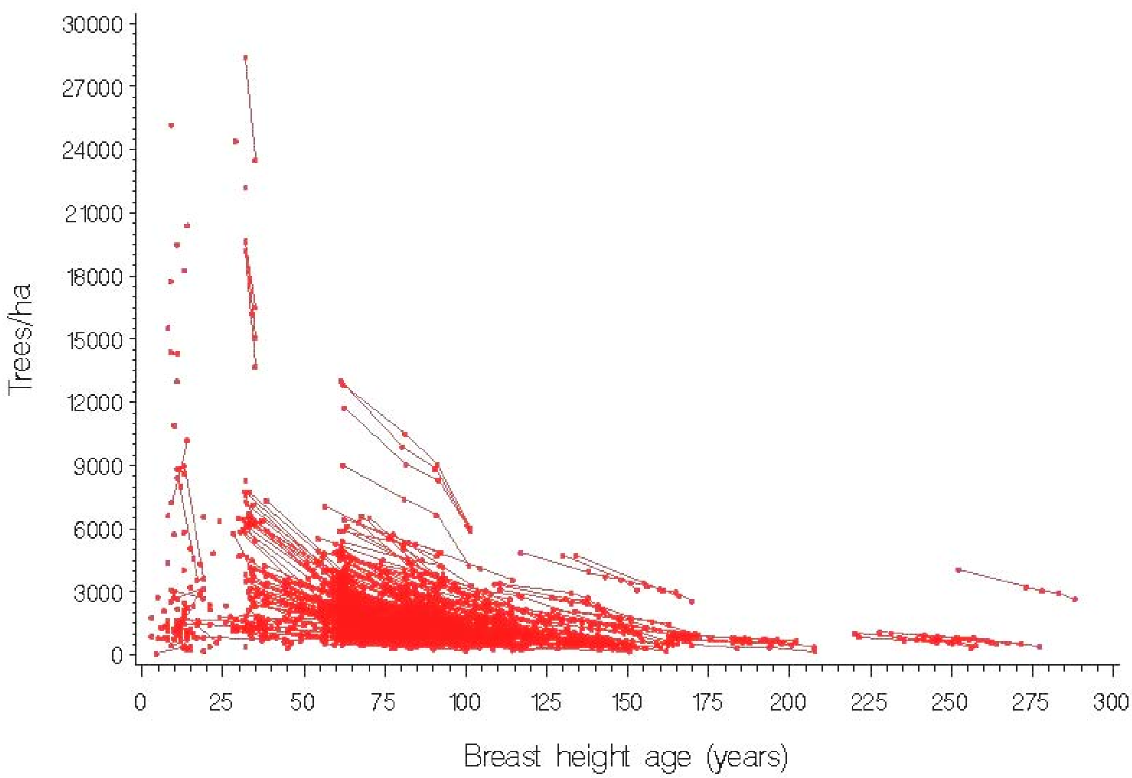


## Growth and Yield Research

The growth and yield of lodgepole pine has been the subject of considerable research and numerous field trials in Canada and the U.S.

Simulation models have been developed for forecasting the growth and yield of fire-origin, post-harvest and managed stands. Of particular relevance to lodgepole pine in Alberta is the work by the Alberta government in developing GYPSY, and the B.C. Ministry of Forests TASS and TIPSY systems (the development of which drew heavily on Alberta data). A major weakness in most modeling systems has been a lack of appropriate data for the development and verification of early stand dynamics. Currently unpublished work by ASRD and Weldwood of Canada is at least partially remedying this (see Figure 2).

**Figure 2. Data used for developing mortality functions in GYPSY**




In British Columbia, Johnstone and Van Thienen (2004) reported results from 11 long-term experiments established in interior B.C. since 1982 to determine the effects of pre-commercial thinning on growth over a range of ages, site and stand conditions. Work in B.C. by Mitchell and Mitchell and Goudie (1980), Goudie (1996), Farnden and Herring (2002), Brockley (2001) and others have shed important light on repression and opportunities for nutrition and density management.

In Alberta, the Canadian Forest Service (CFS) commenced the establishment and analysis of research trials evaluating the growth response of lodgepole pine to thinning and fertilization in 1938 (see Table 1). All trials are in previously unmanaged fire-origin stands. However, they provide important insights relevant to the management of post-harvest stands.

**Table 1. Historic research trials established in Alberta by the Canadian Forest Service**

| *Title / Location* | *Established* |
|---|---|
| Lodgepole pine pre-commercial thinning, Mackay | 1954 |
| Spacing trials – 7 year old fire origin stand of lodgepole pine, Gregg River | 1963/64 |
| Spacing trials – 28 year old fire origin stand of lodgepole pine, Gregg River | 1984 |
| Thinning and fertilization of 40-year-old semi-mature lodgepole pine, McCardle Creek | 1984-85 |
| Early development of lodgepole pine after three different mechanical thinning treatments, Swan Lake | 1977 |
| Ricinus thinning | 1975 |
| Fertilizing after thinning 70-year-old lodgepole pine, Clearwater | 1968 |
| Juvenile spacing of 25-year-old lodgepole pine, Teepee Pole Creek | 1967 |
| Strip thinning of lodgepole pine, Teepee Pole Creek | 1966 |
| Development of a 77-year-old lodgepole pine stand following heavy thinning, Kananaskis | 1941 |
| Various thinnings based on European practices, Kananaskis | 1938-39 |
| Economic possibilities of commercial thinning in an 88-year-old lodgepole pine, Kananaskis | 1950 |
| Commercial thinning in 85-year-old lodgepole pine, Strachan | 1952 |

Research into growth responses to fertilization in western Canada has most notably been undertaken by the B.C. Ministry of Forests (Brockley 2001), Canadian Forest Service (e.g. Yang 1998), the University of B.C., Alberta government, and Weldwood of Canada..

The FGYA commissioned the Alberta Research Council (ARC) to conduct a literature review and evaluate the opportunities for nutrition and density management in fire-origin stands of lodgepole pine in Alberta (White 2002). The work was undertaken by experts in silviculture and forest nutrition from the ARC and the University of Alberta. The report[1] reviews and summarizes much of the relevant growth and yield research conducted on lodgepole pine in north America and elsewhere.

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[1] Available for downloading at: http://www.fmf.ca/pa_FGYA.html

## Evidence of Enhanced Productivity in Regenerated Stands

Over the last 20 years, evidence has accumulated that lodgepole pine stands, regenerated after harvesting, differ considerably from their fire-origin predecessors in terms of productivity and other characteristics. A comparison of the site indices between fire-origin and regenerated stands on Weldwood's forest management area in west-central Alberta indicated a site index increase in regenerated stands of 25 to 30% (Udell and Dempster 1987). The study used paired-plot techniques and stem-analysis based growth intercept and site index models. Subsequently, other studies were conducted in British Columbia and Alberta following the same methodology, with the same or slightly modified field sampling procedures (e.g. Goudie 1996; Nigh and Love 1997; Nussbaum 1998; The Forestry Corp 2002).

Inherent weaknesses in the methodology raised concerns over the stability of early estimates and related over-estimation of performance (Magnussen and Penner 1996). The sampling locations used by Udell and Dempster were re-examined by Huang *et al* (2004), who concluded that the apparent increase in site index is not a short-term artefact, and that post-harvest lodgepole pine stands are growing significantly faster than their fire-origin counterparts. Figure 3 shows the rate of change in post-harvest site index estimates over time. More recent and currently unpublished evidence from permanent sample plots and long-term spacing trials provides further re-assurance that the observed effects were not the result of methodological limitations. Encouraging as these results are, the concern of the original authors (Udell and Dempster 1987), that the challenge will be to husband these productive young forests through to maturity, has not been assuaged.

## Ongoing Work in Alberta

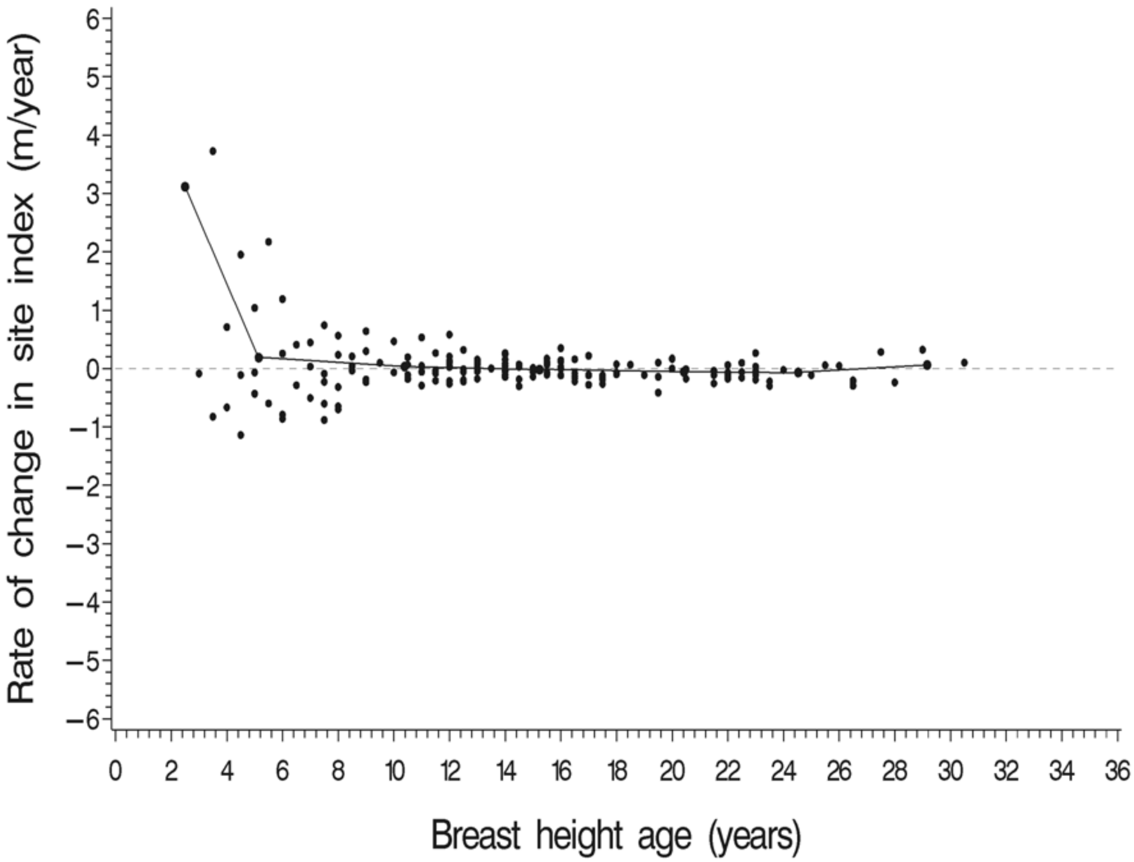
Although considerable progress has been made in forecasting the growth and yield of lodgepole pine in managed stands, significant knowledge gaps and uncertainties confront planners and silvicultural practitioners.

Nine timber companies holding forest management agreements in Western Alberta created the Foothills Growth and Yield Association (FGYA) in 2000. The Alberta Department of Sustainable Resource Development (ASRD) and the Foothills Model Forest participate as non-voting members. The Foothills Model Forest is the coordinating agency, administering the Association on behalf of the other members. The Association has a formalized collaborative arrangement with the CFS, and currently informal working arrangements with a number of other agencies including the University of Alberta Centre for Enhanced Forest Management (CEFM), and the B.C. Ministry of Forests Research Branch. The mandate of the Association is to continually improve the assessment of lodgepole pine growth and yield in managed stands.

Projects initiated by the Association and its partners include:

- *Lodgepole pine regeneration trial*: to assess the development of lodgepole pine, regenerated after harvesting, in relation to site, initial spacing of planted stock, natural ingress and mortality, competing vegetation, and density control.

**Figure 3. Rate of change in post-harvest site index estimates over time (Huang *et al*, 2004)**




- *Comparison of pre-harvest and post-harvest productivity* on a variety of ecological sites: involving contemporaneous sampling of paired-plots in regenerated and parent stands, in combination with analysis of time-series data from permanent sample plots measured before and after harvesting.
- *Cooperative management of historic research trials*: the Association has entered into an agreement with the CFS and the Alberta provincial government for the maintenance and protection of the trials, periodic re-measurement, analysis, synthesis and reporting of results, and interpretive signage.
- *Nutrition and density management*: initiated this year, the project will address gaps in the knowledge required to enhance lodgepole pine growth and yield through nutrition and density management.

Other important Alberta initiatives relevant to enhanced management of lodgepole pine include:

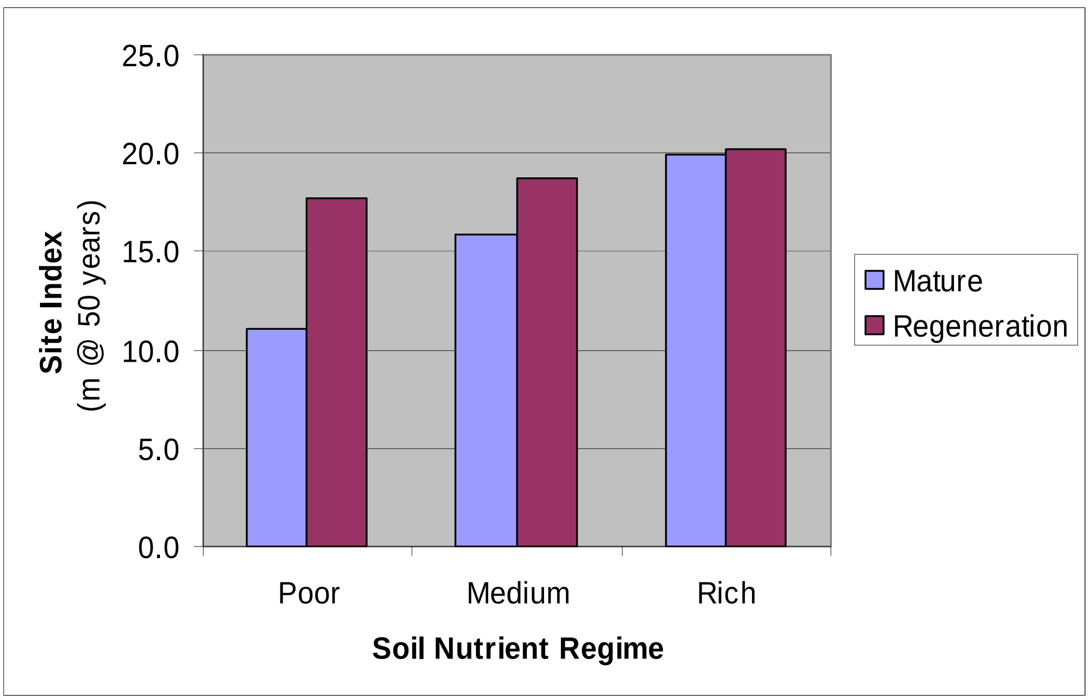
- Climate effects on productivity (ASRD and CFS);
- Enhancement and validation of growth and yield models for managed stands (FGYA, ASRD, Weldwood);

- Repression, crown shyness and water transport (CEFM);
- Development of yield-linked regeneration standards (ASRD and industry).

**Trends in Post-harvest Stands**

The recent site index comparison conducted by the FGYA, based on paired plots in adjacent fire-origin and post-harvest stands, indicated an average upward shift in site index of 24% in stands regenerated after harvesting. Little or no site-index increase was observed on "rich" sites (classified according to Beckingham *et al* (1996) as having high soil nutrient status). On "poor" sites increases reached over 60% (see Figure 4). Data from permanent sample plots, which had been measured both before and after harvesting, also demonstrated substantial shifts in site index following harvest. There were insufficient permanent sample plot data to validate the site interaction indicated by the paired-plot data.

**Figure 4. Average site indices by soil nutrient regime**




It is postulated that post-harvest stands on medium and poor sites are becoming established at substantially lower densities (stems per ha) than did their fire-origin predecessors. Results from spacing trials in Alberta and related research in British Columbia suggest that the site index increases may be attributed to lower initial densities in post-harvest versus fire-origin stands (and hence less height repression resulting from inter-tree competition). This is not definitively verifiable, because no data were available to confirm the initial densities of the mature stands studied. However, recent work by ASRD working in cooperation with Weldwood of Canada (Huang *et al* in preparation) has resulted in a density / mortality function that we believe can be applied with some confidence to the retrospective projection of probable initial densities. This function takes the following form:

$$N = b_0 + (SDF - b_0) \cdot \left( \frac{1 + \exp[b_1 + b_2 \ln(50+1) + b_3 \ln(SI - 1.3)]}{1 + \exp[b_1 + b_2 \ln(bhage+1) + b_3 \ln(SI - 1.3)]} \right)$$

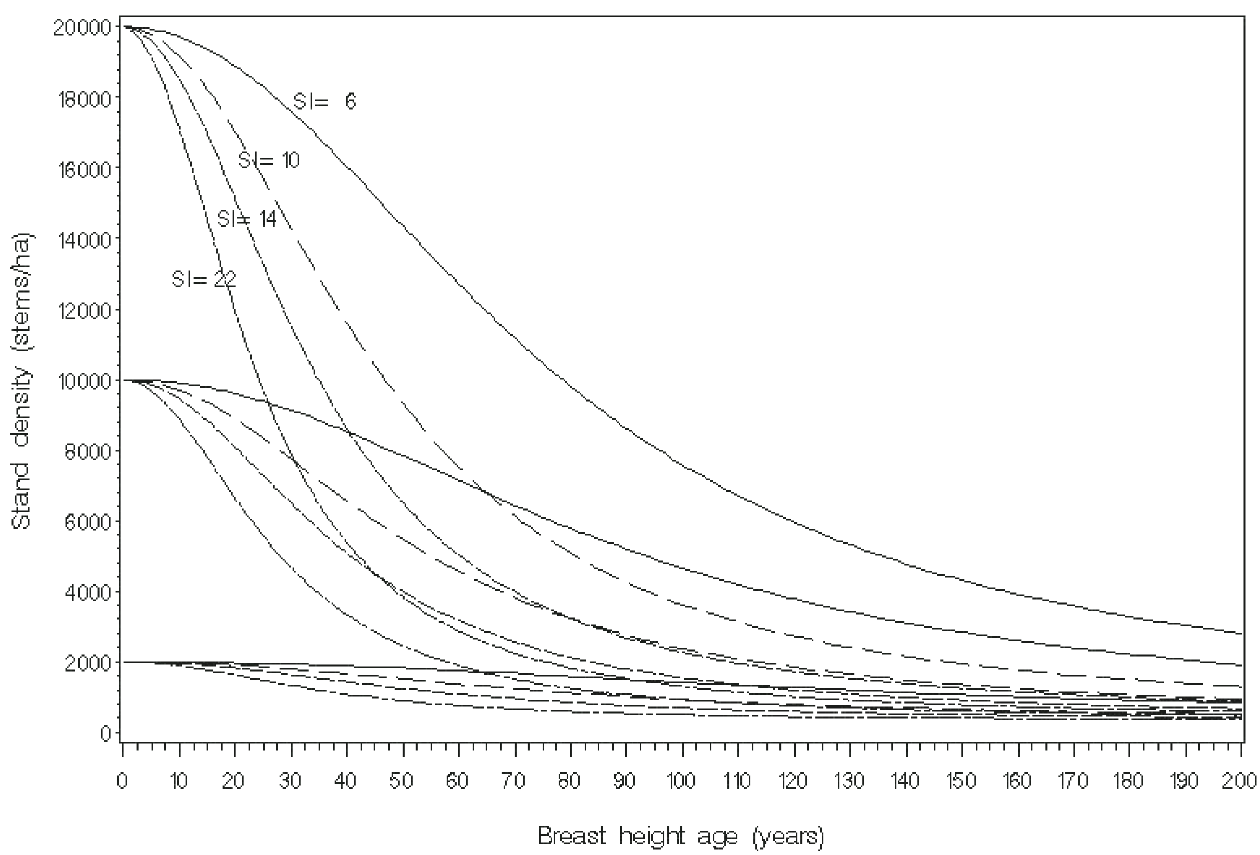
where the SDF (stand density factor) is defined as the stand density (trees/ha) at a reference breast height age of 50 years, and $b_0$-$b_3$ are model parameters predicted by the following equations:

$$b_0 = (15184.37 + SDF)/(50+1) \qquad b_1 = \frac{-14.1979}{(\sqrt{SDF/1000})^{0.086639}}$$

$$b_2 = 2.14574 \cdot \left( \frac{SDF}{1000} \right)^{1/SDF} \qquad b_3 = 2.14574$$

The SDF in the density / mortality function acts like SI in site index models. It provides the basis for stand density projection at any point in time. Example density trajectories generated from this function at selected initial densities and site indices are shown in Figure 5.

**Figure 5. Lodgepole pine mortality trajectories at different initial densities and site indices**

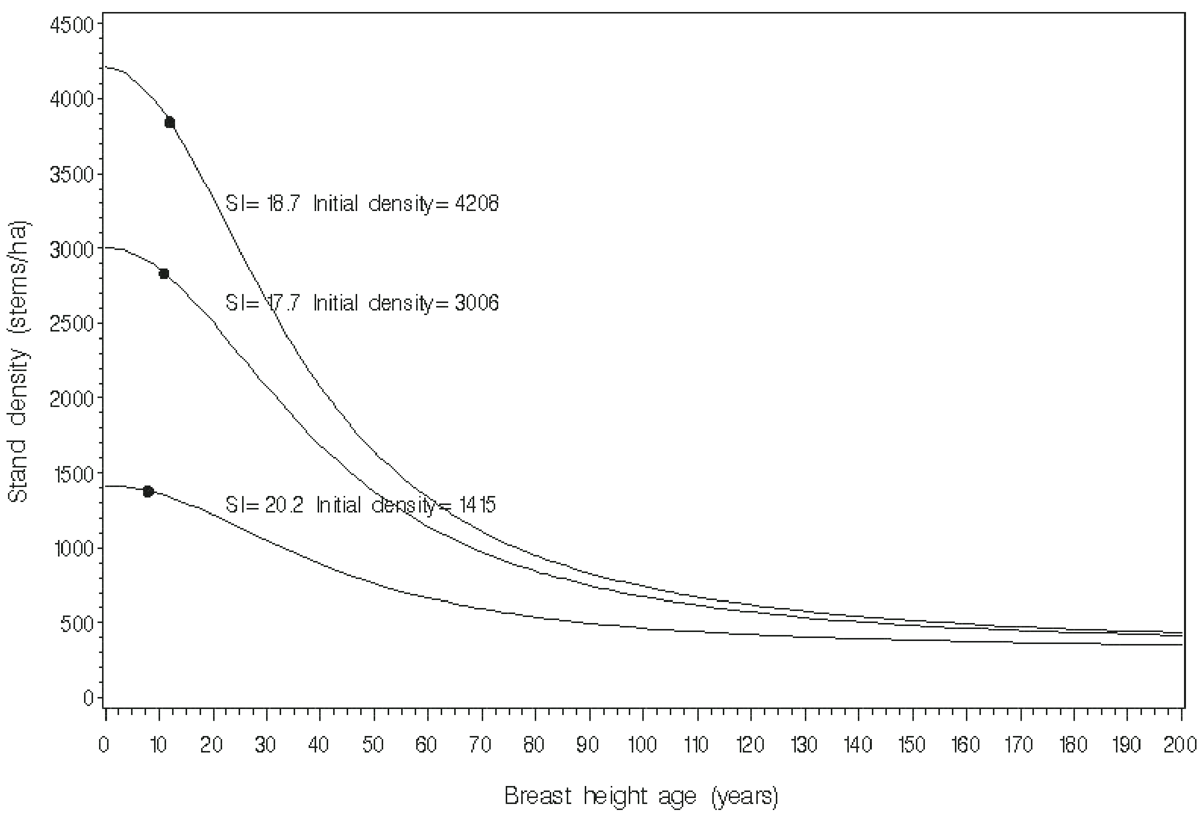


The stand density function developed by Huang *et al* was used to estimate initial densities from current density, site index and age for each of the soil nutrient and stand origin categories shown in Figure 4. GYPSY was then used to simulate future stand development, and to predict mean annual increment (13/7 utilization standard[2]) and age of m.a.i. maximization. Results are shown in Table 2.

**Table 2. Estimated productivity and initial densities for regenerated and fire-origin stands**

| Soil nutrient regime / stand origin | Site index (m @ 50 years) | B.H. age (years) | Current density (stems/ha) | Estimated initial density | Max. mai (13/7) | Culmination age (total) (years) |
|---|---|---|---|---|---|---|
| **Poor-mature** | 11.0 | 120 | 2287 | 18773 | 1.63 | 130 |
| **Poor-regen** | 17.7 | 11 | 2833 | 3006 | 3.21 | 66 |
| **Medium-mature** | 15.9 | 113 | 1176 | 11057 | 3.11 | 87 |
| **Medium-regen** | 18.7 | 12 | 3844 | 4208 | 3.74 | 66 |
| **Rich-mature** | 19.9 | 103 | 504 | 1878 | 3.56 | 61 |
| **Rich-regen** | 20.2 | 8 | 1378 | 1415 | 3.42 | 61 |

**Figure 6. Stand density trends for regenerated stands based on observed values**



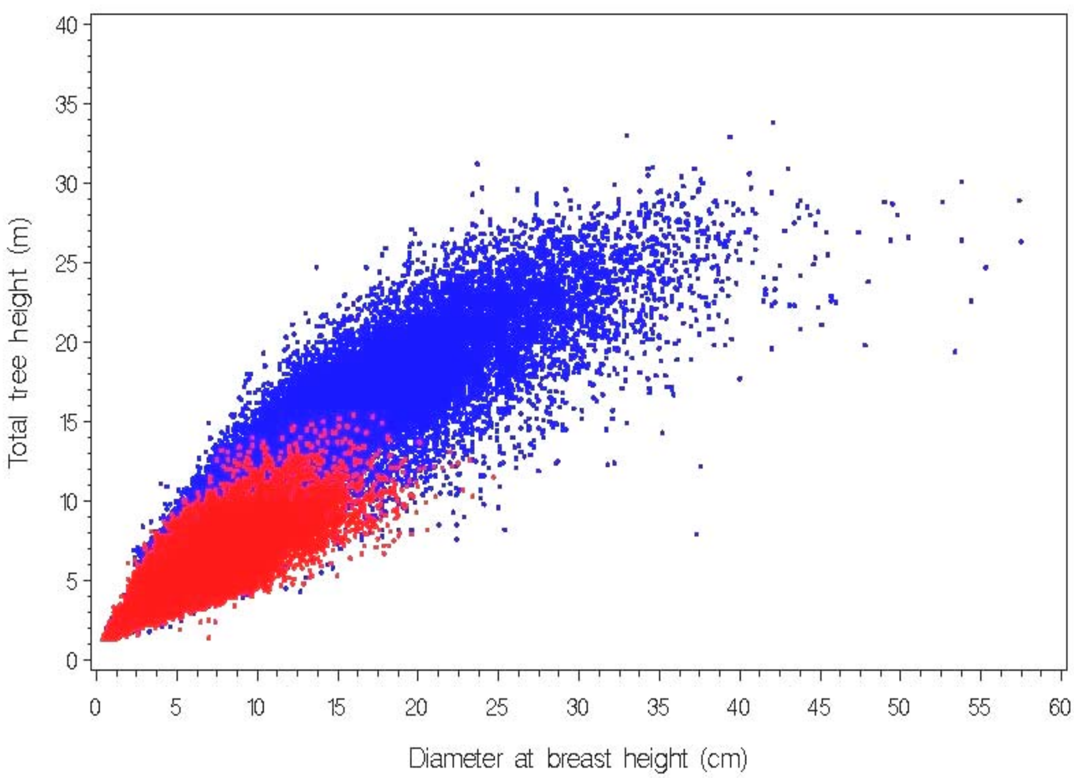

[2] Merchantable volume based on a 13 cm minimum outside-bark stump diameter, 7 cm minimum top diameter inside-bark, minimum merchantable length 2.44 m, and 0.3 m stump height.

Overall there is little difference between mature stands and regeneration in the site indices and initial densities forecast for rich sites, but the differences increase on the medium and poor sites. Forecast volume productivity increases 97% on poor sites, and 20% on medium nutrient regimes, in regenerated stands, with concomitant reductions in years to reach mai culmination. On rich sites, volume production is forecast to be similar, or even slightly less, in regenerated versus fire-origin stands. Low initial densities may have limited coniferous production in the fire origin stands, and be similarly limiting production in the regeneration. The density trajectories shown in Figure 6, simulated for regenerated stands by the density / mortality function, attest to this conjecture. Current regenerated density on rich sites may be sub-optimal and coniferous stocking insufficient to fully utilize the site (see also Figure 8 and further discussion below).

It is tempting to speculate that on the rich sites productivity in natural stands has been less limited by intra-specific (self-thinning) competition relative to the medium and poor sites. On rich sites inter-specific (brush and aspen) competition is more prevalent, which may in part explain Monserud and Huang's results regarding the mapped distribution and productivity of lodgepole pine in Alberta.

The substantial shifts in height growth and densities between fire-origin and post-harvest stands may be accompanied by related changes in taper and crown characteristics. Figure 7 shows trends of height and diameter values observed in fire-origin (blue) versus regenerated (red) trees on Weldwood's Alberta forest management area (courtesy of Weldwood of Canada).

**Figure 7. Trends in tree height and diameter in fire-origin versus post-harvest stands**



## Opportunities, Threats and Uncertainties

Some general comments on thinning and fertilization will be followed by some more specific observations regarding density management in young stands.

*Thinning and Fertilization*

In reviewing lodgepole pine thinning trials throughout western North America, White (2002) noted that the majority of studies showed a negative total basal area growth response to thinning. An increase in average stem diameter increment was observed in all studies reviewed, but this was typically offset by the smaller number of trees retained on site. Consistent with established thinning theory, the increase in diameter increment of residual trees can result in gains in merchantable volume, or reductions in rotation length, depending on the tree utilization standard applied and the time of final harvest. In the studies where gains in net basal area increment were observed, the increase was generally attributable to less mortality occurring in the treated plots than in the controls. The idea that yield gains can be achieved by offsetting mortality has prompted both experimental and operational interest in mid and late-rotation thinning in Alberta.

Caution is prudent in the development of commercial thinning prescriptions since:

- Expected benefits from larger trees may not be realized because of changes in milling technology;
- The danger of insufficient stocking resulting from mortality agents is increased;
- Determining which natural stands will respond is difficult and uncertain;
- Where gains in tree size or yield are achieved, they may not be economically viable.

Opportunities for increasing total volume productivity through thinning are for the most part limited to early interventions in stands where height growth will otherwise be repressed by excessively high densities. Spectacular increases in height growth have been demonstrated possible though density control in such stands, and are readily apparent in several of the CFS spacing trials in Alberta mentioned previously. In B.C., Farnden and Herring (2002) demonstrated up to an 8 m site-index increase to result from a combination of thinning and fertilization in stands severely repressed by over-stocking. However, in Alberta operational application of pre-commercial thinning has been limited, for a combination of possible reasons including:

- Post-harvest stands are usually regenerating at average densities less than those predicted to induce serious repression;
- Concerns over forest health deterioration;
- High cost of pre-commercial thinning in fire-origin stands;
- Limited or uncertain allowable-cut effect.

Nitrogen deficiencies are widespread throughout much of the range of lodgepole pine in western Canada, and create opportunities for achieving growth increases through fertilization. Trials have been conducted over a range of sites and ages, with and without thinning, with and without other nutrient additions, and using various nitrogen sources. Brockley (2001) reviewed over 30 trials in B.C. and Alberta, and noted that volume growth responses over a 6 year post-treatment period ranged from negative to over 50% relative to controls, averaging around 30%, or 9 $m^3$ / ha for an application rate of 200 kg N/ha. Although height (as distinct from basal-area) growth response has generally been relatively small, nitrogen fertilization has been demonstrated to assist in release from height repression. Stands thinned at the time of fertilization have generally responded better to fertilization than those non-thinned or thinned earlier. The uncertainty of response at the individual stand level has resulted in initiatives to enhance diagnosis. Threats associated with fertilization include damage by mammals and snow-press.

*Density Management in Young Stands*

Post-harvest stands are usually regenerating at average densities less than those predicted to induce repression, and this represents a major potential for increased productivity. It is tempting to conclude that such increases can be expected without further intervention.

However, over-stocking has not been totally eliminated, and perhaps more importantly, on some sites under-stocking is of greater concern. Figure 8 shows GYPSY simulations for rich, medium and poor sites regenerated at a range of initial densities bracketing those reported in Table 2. The black curves represent volumes predicted for initial densities of 1111, 1600, 2500, and 4444 stems per ha[3]. (The predicted volumes increase with initial density over this range.) The red curves represent the average densities reported Table 2 for regenerated stands. Results suggest that average regeneration densities are sub-optimal for maximizing merchantable volume yields on the best sites. All sites sampled had previously been classified as satisfactorily re-stocked during establishment surveys usually conducted 4 – 8 years after harvest.

Informal observations of regenerated stands by FGYA, CEFM, and other experts further indicate that the density or stocking of healthy crop trees in regenerated stands are generally sub-optimal for the application of crop plans aimed at increasing yields through intensive management.

More work is required to evaluate the relationship between stocking (site occupancy) and density on regenerated versus fire-origin stands. Even on medium sites, where relatively high average densities are being achieved (see Figure 8), gaps, stocking failures and incomplete site occupancy are encountered. Both TASS and GYPSY predict increases in volume production at initial densities above those shown in Figure 8. Substantial height repression is not typically induced at initial densities below 10,000 stems per ha (Goudie 1996, Huang *et al* 2001).

Biotic damage by gall and blister rusts, mammals, root rot, root-collar weevils, and pitch blister moths, is prevalent in immature post-harvest lodgepole pine regeneration in west-central Alberta, and there is evidence that the incidence of at least some of these pests may be exacerbated by low stand densities (Ives and Rentz 1993). Volney and Mallett (1998) suggest that the general principle for guiding the management of young stands, of emulating natural stand conditions, will minimize losses due to pests. Recognizing that this is not always possible, they stress the need for integrated pest management and the development of biological and silvicultural control methods. Our results suggest that current silvicultural practices are not emulating natural stand conditions, especially in relation to initial densities. This, in combination with no widespread operational application of integrated pest management, creates a potential for stocking failures and productivity loss.

Harvesting, public reluctance to accept widespread herbicide use, and (perhaps) climate change are combining to create a species shifts towards aspen on some of the better lodgepole sites.

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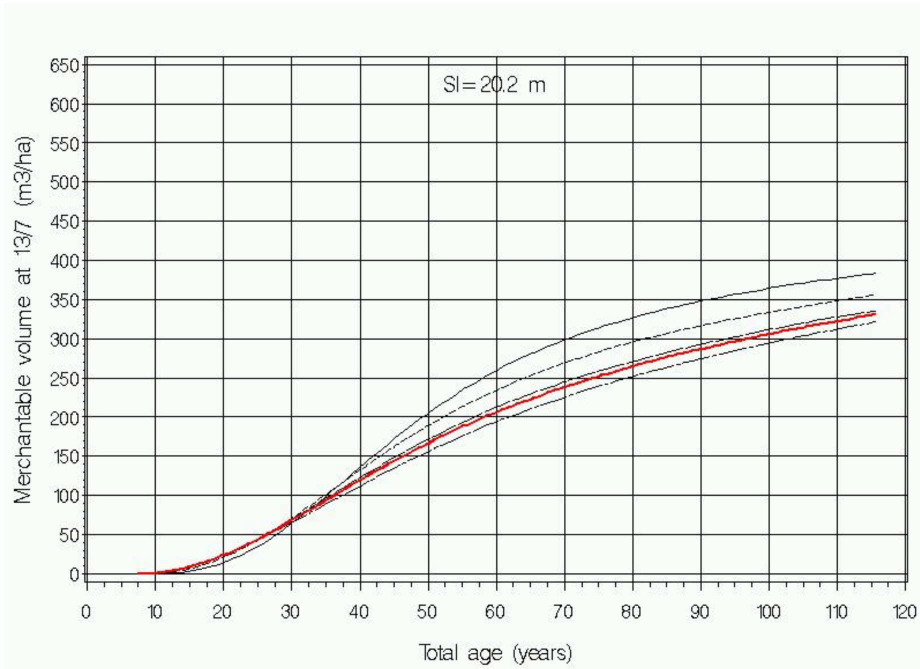
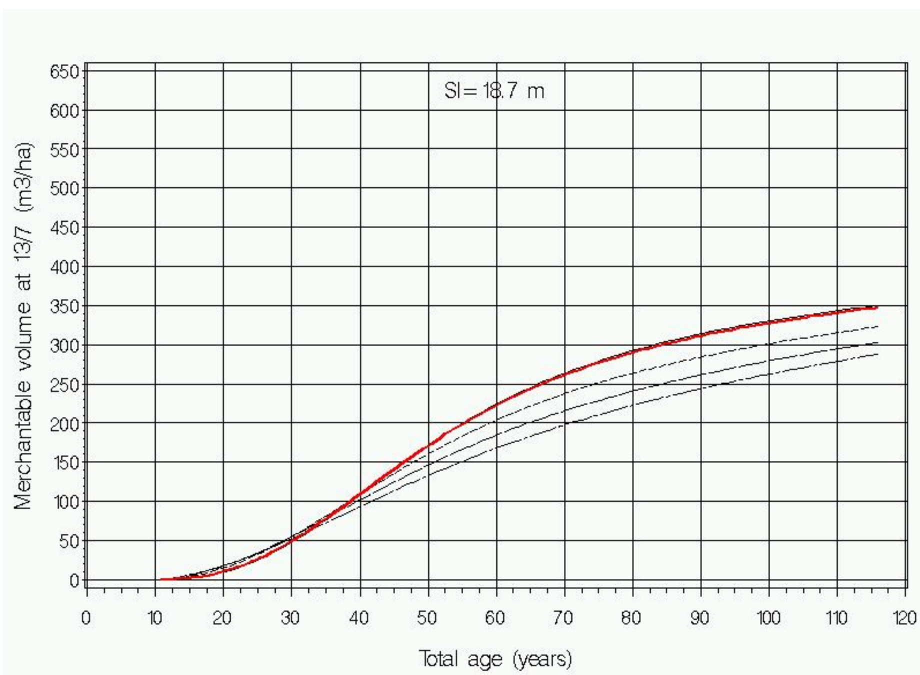
[3] The densities simulated are being experimentally tracked in the FGYA lodgepole pine regeneration trial.

**Figure 8. Projected volumes for stands regenerated at different initial densities**

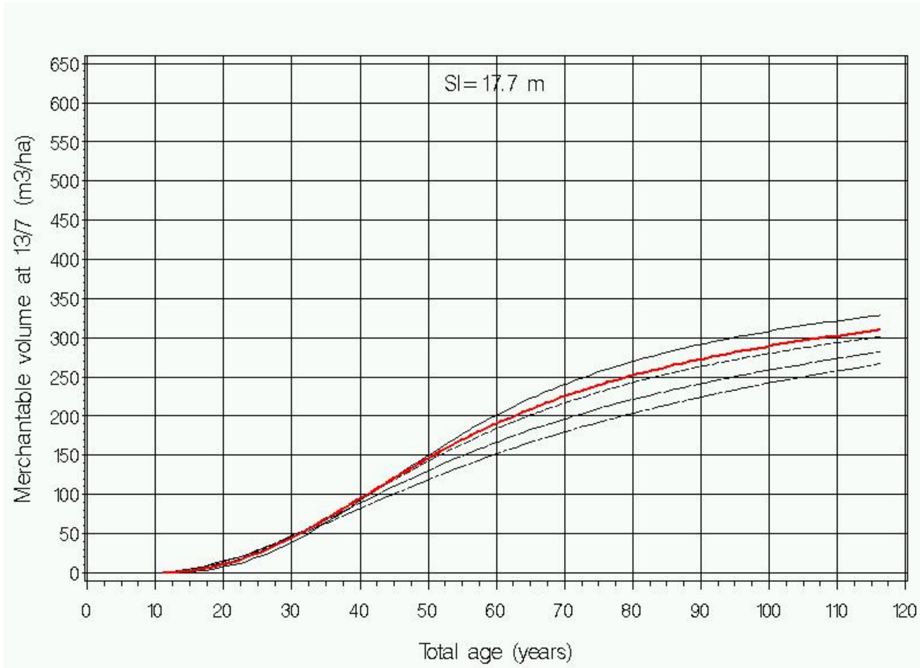
**(a) Rich site**




**(b) Medium site**



**(c) Poor site**




(Black curves are volumes predicted for initial densities of 1111, 1600, 2500, and 4444 stems per ha. Red curve represents densities reported in Table 2 for regenerated stands.)

The impacts of climate change on productivity and probabilities of catastrophic loss through fire and mountain pine beetle are beyond the scope of this paper, but represent threats or uncertainties that need to be factored into the density management of lodgepole pine.

Increased taper and growth rates associated with lower stand densities (stems per ha) will affect wood properties, and are likely to result in lower wood densities, lower tensile strengths, and longer fibre lengths relative to fire origin stands (Weldwood of Canada, 2002).

We conclude that the main opportunity for increasing timber production through early density management is to encourage high initial densities and site occupancy, without exceeding density thresholds resulting in the onset of repression. Optimum densities for maximizing timber production at typical Alberta utilization standards are probably in excess of 5,000 stems per ha. Since it is unlikely that these will be achieved economically by planting, emphasis needs to be placed on harvesting and site preparation techniques promoting natural regeneration (e.g. Bancroft, undated).

## Priorities for Enhanced Management

We suggest the following areas merit the attention of planners, researchers, and silvicultural practitioners.

*Forecasting and Monitoring*

The progress being made in the development of improved growth models for developing managed stand yield tables is encouraging and should be pursued diligently. However, while our ability to forecast yield as a function of site and early stand conditions is improving, with few exceptions little modeling attention has been paid to the reforestation phase of stand development i.e. quantitative forecasting of stocking, density, survival, ingress, and growth response relative to ecosite, harvesting method, planting density, competition, and vegetation management. The FGYA regenerated lodgepole pine field trial, established between 2000 and 2002, was designed to address this shortfall. Maintenance and analysis of existing trials, and selective establishment of new ones, are filling information gaps on treatment responses in later phases of stand development.

Post-harvest stands are growing under different conditions to those of their predecessors. Forecasting and monitoring must go hand in hand. Several Alberta tenure-holders have established permanent sample plot systems. A grid–based framework coordinated on a provincial level, as proposed by Huang *et al* (2004), provides a comprehensive option for long-term monitoring of growth.

The Alberta government's intent to encourage the scientific development of stratum specific regeneration standards linked to growth and yield will place further priority on the development of reliable forecasting tools, and monitoring to ensure early corrective action when targets are not met.

*Risk Management*:

We believe that emphasis should be placed on the development and implementation of cost-effective harvesting, site preparation, and propagation techniques that are capable of producing high initial densities and stocking levels, thus offsetting risks of irregular mortality while maintaining options for subsequent silvicultural interventions.

Some noteworthy approaches for managing pests in young stands have been proposed or developed (e.g. pre-treatment threat assessment, tree improvement to select for gall rust resistance, biological control of gall rust, silvicultural strategies to limit *Armillaria* root disease and rootcollar weevil.) A higher emphasis is warranted on the application, development and integration of pest management approaches. Observed and forecast stand structures should also be linked to risk rating systems and spread models for fire and mountain pine beetle.

*Integration of Knowledge*

Improved risk management and silvicultural decision-making requires considerable interdisciplinary expertise and the integration of knowledge from the specializations of silviculture, genetics, growth and yield, fire behavior, and pest management.

*Intensive Management*

There is no doubt that nutrition and density management holds promise for enhancing fibre production in lodgepole pine, and there is good evidence that selective intensification of management is economically viable. However, its successful application to post-harvest stands will require a rigorous approach to crop planning and initial crop establishment.

## Conclusion

Knowledge gained from Alberta studies and elsewhere suggests that regeneration practices following harvesting are capable of increasing fibre production relative to that of fire-origin stands. Effective realization of this opportunity will require improved forecasting, risk management, interdisciplinary cooperation, selective intensification of management, and careful monitoring. Ongoing research will shed more light on specific opportunities for enhanced fibre production. In the meantime, operational emphasis should be placed on achieving high levels of site occupancy during reforestation and reducing risks of stocking failures.

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