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Stand density management diagrams for lodgepole pine, white spruce and interior Douglas-fir

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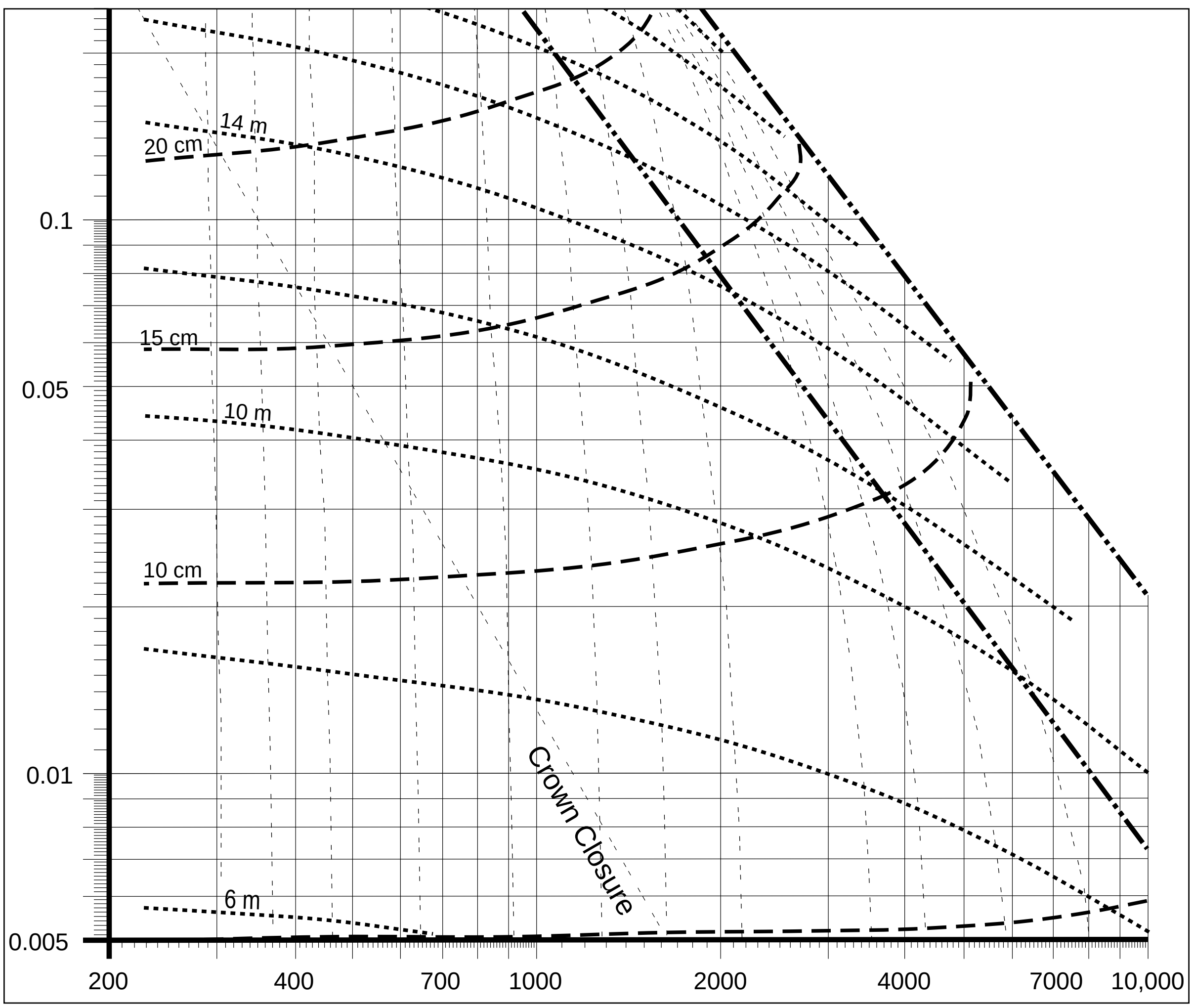

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Abstract

Density manipulation is one of the most powerful tools available to silviculturists to achieve a broad range of silvicultural objectives. One of the most effective methods of planning density management in even-aged stands is through the use of stand density management diagrams. These diagrams graphically depict the temporal relationships between stand density, top height, quadratic mean diameter and mean tree volume. They allow the user to develop and project crop plans through time, to determine the optimum timing of thinnings, to determine the operational feasibility of thinnings, and to contrast potential outcomes from a number of stand management regimes. The stand density management diagrams for lodgepole pine, white spruce and interior Douglas-fir in this report were derived from managed stand yield tables produced by TASS, an individual tree, distance-dependent growth model. The report describes their use in planning thinning regimes and making preliminary yield estimations.

Résumé

L’un des outils les plus puissants dont disposent les sylviculteurs pour atteindre une vaste gamme d’objectifs est la manipulation de la densité. Les diagrammes d’aménagement de la densité de peuplement constituent l’une des méthodes les plus efficaces de planification de l’aménagement de la densité dans des peuplements équiennes. Ce sont des graphiques qui montrent les rapports dans le temps entre la densité du peuplement, la hauteur moyenne des arbres dominants, le diamètre de la tige de surface terrière moyenne et le volume moyen de l’arbre. Ils permettent a l’utilisateur d’établir et de prévoir des plans parcellaires de régénération dans le temps, de fixer le calendrier optimal des éclaircies, d’établir la faisabilité opérationnelle des éclaircies et de comparer les résultats éventuels d’un certain nombre de traitements sylvicoles. Dans le présent rapport, les diagrammes d’aménagement de la densité de peuplement du pin tordu, de l’épinette blanche et du douglas bleu ont été établis à partir des tables de rendement de peuplements aménagés calculées par le TASS, un modèle qui prévoit la croissance des arbres individuels en fonction de l’espacement. Le rapport décrit leur rôle dans la planification des traitements d’éclaircie et dans l’estimation préliminaire des rendements.

1.0 Introduction

Density manipulation is one of the most powerful tools available to silviculturists to achieve a broad range of stand level objectives. Stand attributes such as height/diameter ratios, crown length, width and percent cover, branch/knot size, and tree vigour are strongly influenced by stand density. In turn, these attributes affect wood quality, quantity and value, resistance to insects and disease, stand value for wildlife habitat, range and recreation, and hydrologic storage of snow packs. The choice of a density management regime is therefore critical for achieving stand and ultimately forest level objectives.

One of the most effective methods of planning density management in even-aged stands is through the use of Stand Density Management Diagrams (SDMDs). These are graphical representations of stand development which, in various formats, illustrate the interactions between density or some other measure of stocking, and various stand parameters such as mean diameter, top height and volume. When used in conjunction with height over age (site index) curves, the factor of time can also be integrated. These diagrams allow a silviculturist to compare stand development trajectories for various establishment densities and thinning regimes on a given site.

The SDMD configuration used in this report is similar to that proposed by Drew and Flewelling (1979) for coastal Douglas-fir. The diagrams for lodgepole pine, white spruce and interior Douglas-fir (Figure 1 and Appendix I) are plotted from variable density managed stand yield tables generated by the Tree And Stand Simulator (TASS), an individual tree, distance-dependent growth model developed by the British Columbia Ministry of Forests (Mitchell 1975). The use of this model to plot the diagrams eliminated the need to perform complex mathematical analyses of large data sets, and has resulted in stable growth relationships that reflect those of the computer-based growth and yield tools already in use by the B.C. Ministry of Forests. These diagrams should be considered a complement to those computer-based tools rather than a replacement.

This report is aimed at practicing silviculturists. It is anticipated that the information contained herein will be useful in making informed decisions for stand level crop planning.

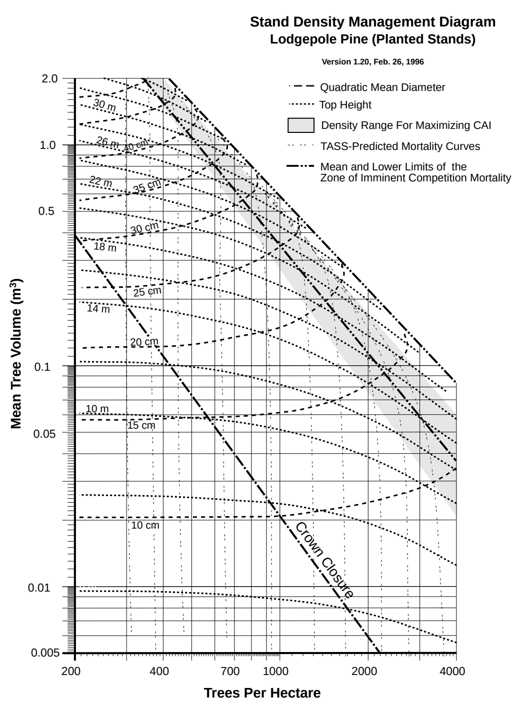

Figure 1. Stand density management diagram for planted white spruce stands. Full page versions of all six diagrams can be found in Appendix I.

2.0 Basic principles

The SDMD proposed by Drew and Flewelling (1979) is similar to those developed by Japanese researchers (Ando 1962, 1968; Tadaki 1963; Aiba 1975a,b) which in turn were based on the principle of self-thinning developed by Yoda et al. (1963). This principle describes a maximum plant size/density relationship which dictates competition related self-thinning within a stand of relatively uniform plants. When mean tree biomass, or bole volume as an acceptable substitute (Drew and Flewelling 1977), is plotted against density on a double logarithmic scale (Figure 2A), there is a maximum size-density limit represented by a line with a slope of approximately -3/2. At any given density, there is a maximum average tree size that can be achieved. Early in stand development, average tree size can increase without density-related mortality. As stands begin to approach the maximum size-density limit, further increases in tree size must be accompanied by decreases in density (Figure 2B). With continued tree growth, mortality accelerates such that a line plotting the size/density relationship over time becomes parallel to the -3/2 maximum density line. Most SDMDs include both the maximum density line and a line indicating the onset of competition based mortality. This second line is often called the lower limit of the Zone of Imminent Competition Mortality (ZICM), and approximates the point at which self-thinning starts to dramatically accelerate.

In the diagrams in this report, the maximum size-density relationship is not presented, but is replaced by a line drawn asymptotic to the average condition rather than the maximum (Figure 2C). This mean limit of the ZICM represents the maximum size-density relationship of the “average” stand as modelled by TASS. It is important to note that roughly half of all actual stands may have real trajectories that lie above this line (see section 9.0).

Stand top height is illustrated on the diagrams in a series of isolines which slope downwards moving from left to right (Figure 2D). Height is important in these diagrams because, under most conditions, height growth of trees is independent of stand density[1]. This principle is important as it allows the use of height growth as a measure of site productivity.

In addition to illustrating an important stand size attribute, therefore, these lines can be used to incorporate time, and thus rates of growth, through the use of site index curves (see Appendix II). Knowing the site index of a stand, you can easily use these curves to determine the age at which it will reach a given height. Site index is therefore critical for the application of SDMDs.

The quadratic mean diameter[2] of a stand is illustrated by a series of iso-lines sloping upward from left to right (Figure 2E). Stand diameter is an attribute that is highly sensitive to stand density and hence is often a target for manipulation. Following a height line from right to left, it is readily evident how drastically stand diameter at a given age is altered given changes in establishment density.

Stand density also affects the rate of volume production, or current annual increment (CAI), in a stand. One of three hypotheses on the pattern of this effect as discussed by Smith (1986) is that CAI at a given stage of stand development would be uniform over a wide range of densities, but would decline at low densities due to incomplete site occupancy and at high densities due to overcrowding. This optimum range of densities changes with stand development, and knowing the limits of this range is useful for planning thinning regimes. This pattern is found in the output from the TASS model, and the range of densities over which volume production is maximized is therefore explicitly recognized on the diagrams as a shaded zone.

A final line that is found on most SDMDs is the crown closure line. This line represents the points at which the crowns of trees in stands of different densities start to interact. Below this line, trees behave much like open grown trees, with little or no inter-tree competition. Individual trees exhibit maximum vigor and diameter growth. As trees grow above this line, they experience increasing inter-tree competition, decreasing rates of diameter growth, and increased natural pruning due to canopy shading (Figure 3).

There are two stand density management diagrams for each of the three species covered by this report: one for planted stands and one for natural stands. The differences in the two diagrams for a species reflect the impacts of spacing uniformity. The planted stand diagrams are based on TASS runs which assumed a relatively uniform spacing of trees,

[1] Height growth of lodgepole pine has been demonstrated to decline at densities greater than 10,000 trees per hectare, with increasing effects at greater densities. This effect is commonly referred to as height repression.

[2] Quadratic mean diameter (Dq or QMD) is the diameter of the tree of average basal area.

$$Dq = \sqrt{\frac{\Sigma D_i^2}{n}}$$

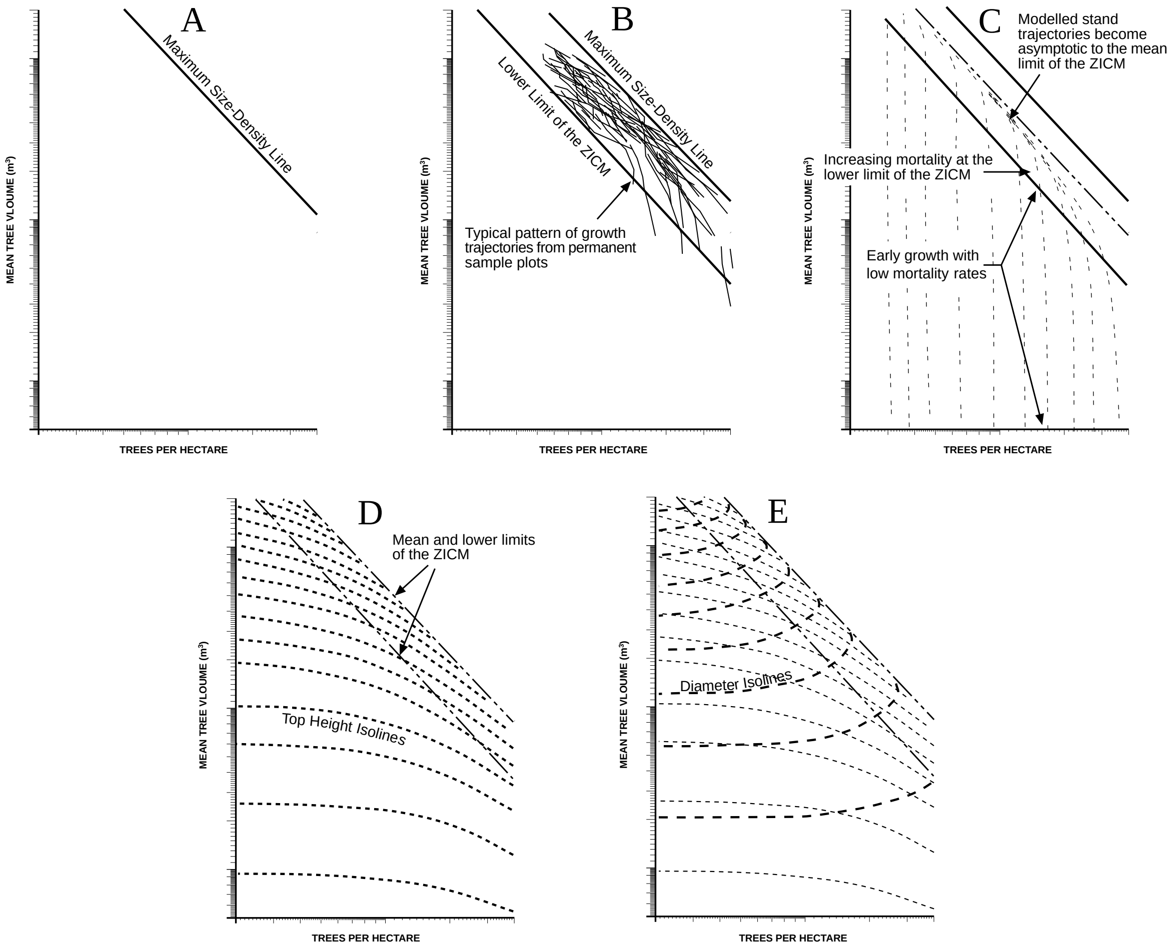

Figure 2. Key components of a stand density management diagram. The maximum density line (A) represents the maximum average tree size that can be achieved at a given density. Above the lower limit of the ZICM (B), growth trajectories of various stands approach and parallel the maximum size-density line, at which point further increases in average piece size must be accompanied by decreases in density. “Average” stand trajectories as modelled by TASS (C) become asymptotic to a line parallel to but lower than the maximum size-density line. In the SDMDs in this report, this line is referred to as the mean limit of the ZICM. As stand trajectories move upward through the diagrams, they intercept various isolines representing stand top height (D) and quadratic mean diameter (E).

in which each tree has roughly the same growing space and competitive conditions.

The natural stand diagram, on the other hand, assumes less uniform spacing with small openings and clumps. In this scenario, trees in the clumps undergo competition-based mortality much earlier than the more open portions of the stand. In the diagrams representing natural stands, there is a less vertical slope to the mortality curves below the lower limit of the ZICM than in the diagrams of planted stands. The result is a difference in the height/diameter/density relationships.

The ZICM is much broader on the natural stand diagrams, reflecting greater spatial pattern heterogeneity; there is a more gradual transition from the lower portion of the diagram which is free of mortality to the area adjacent to the maximum density line. It is also evident that the zone reflecting the range of densities over which CAI is maximized occurs higher in the natural stand diagrams than in the planted stand diagrams. In a perfectly uniform stand of identical trees, it could be expected that the upper limit of this zone would coincide with the lower limit of the ZICM, as any tree mortality would be a loss of merchantable volume and would leave unoccupied gaps in the canopy. In reality, the trees that are dying are much smaller than the true crop

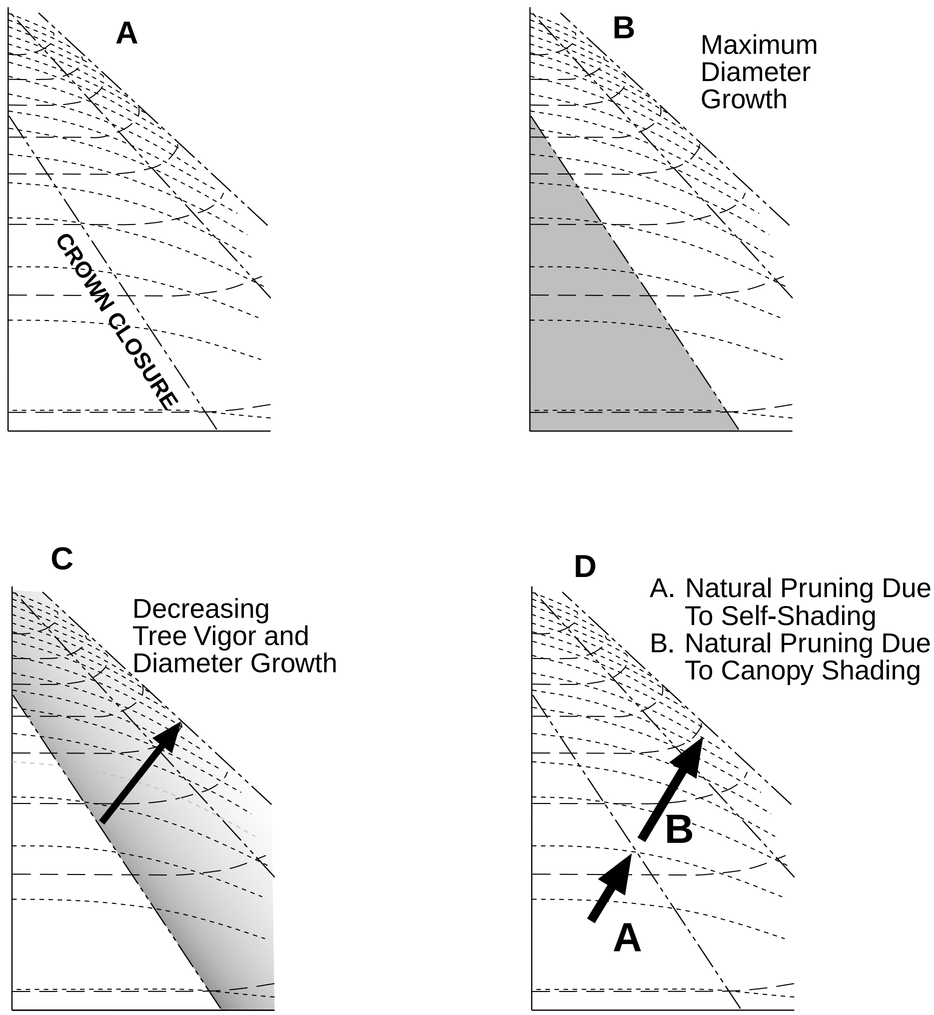

Figure 3. The crown closure line (A) is the point at which individual trees start to compete with each other. Maximum individual tree diameter growth occurs below this line (B), with decreasing individual tree vigor and diameter growth moving from the crown closure line to the maximum size-density line (C). Natural pruning is also maximized by growing a stand in closer proximity to the maximum density line than to the crown closure line (D).

trees and leave little if any growing space unoccupied. Managed stands are more uniform in size than natural ones, so dying trees have more of an effect on CAI. This effect extends to natural stands that have been thinned from below, where the increase in stand uniformity will result in both the lower limit of the ZICM being raised in the diagram, and a lower rate of mortality below the ZICM.

Stand density management diagrams are only suitable for even-aged stands, and within this report only for single-species stands. The diagrams should, however, be useful in mixed stands where a single species is clearly dominant.

With no Operational Adjustment Factors (OAFs) applied, the diagrams reflect the growth relationships of fully stocked research plots with no significant pest problems (Mitchell et al. 1995). Yields suggested by the diagrams are therefore *total potential* yields, and may have to be scaled downward to reflect *merchantable operational* yields (see Section 5.0). The relationships within the diagrams also reflect stands that grow through to harvest without mid-rotation cultural entries. While the fixed height/diameter/density relationships within the diagrams remain stable for stands undergoing early pre-commercial thinning, adjustments in the predictions are required for trajectories which include commercial thinnings (see Section 5.0)

3.0 Diagram construction and evaluation

The relationships between various stand parameters in the SDMDs in this report reflect those of the TASS growth model as expressed in the managed stand yield tables contained in WinTIPSY (version 1.0). The survivorship trajectories and the height and diameter isolines were plotted directly from numerical values in the WinTIPSY output tables, while the ZICM limits and the crown closure lines were inferred from graphed relationships. The TASS model was also used to test the validity of post-thinning stand growth patterns predicted by the SDMDs.

The mean limit of the ZICM was manually plotted as an estimate of the asymptote of the survivorship curves, while the lower limit of the ZICM was placed to reflect the transition from the early stage of development, which is relatively free of competition mortality, to the ZICM. The lower limit of the ZICM in these diagrams attempts to show the same relationship as in other diagrams, but may differ due to methodology and data source.

The lack of a line representing the maximum size-density relationship precludes the use of Drew and Flewelling's (1979) Relative Density Index (RDI), which was defined as the ratio of actual stand density to the maximum stand density attainable at the same mean tree volume. Drew and Flewelling described their lower limit of the ZICM and their crown closure line in terms of RDI, and similar values calculated for other diagrams are useful for comparison. Unfortunately, such comparison is difficult for the diagrams in this report.

The range of densities over which volume production is maximized was determined by calculating CAI's for a set series of densities and top heights. For a given top height, CAI was plotted against stand density. The optimum range of densities for volume production was then determined as that for which CAI was within ten percent of the peak value. When this process was repeated for a number of different top heights and plotted on the appropriate SDMD, a zone was defined which illustrates the range of densities over which volume productivity is maximized for any given top height.

The crown closure line for a particular diagram was determined by joining the points at which the quadratic mean diameter of modelled stands deviated by more than one centimeter from that of an open grown stand of the same top height. It was assumed that all stands regardless of density would have similar individual tree growth patterns up until the point of crown closure. A stand of the lowest density available in the WinTIPSY database could therefore serve as a surrogate for an open grown stand, as it would reach crown closure later than would stands at higher densities.

For each of the three species covered by this report, ten TASS runs were produced to test the validity of growth patterns predicted by the SDMDs. Three different densities were each thinned at three different heights, and compared to a low density unthinned stand. Post thinning densities were chosen to match the unthinned stand at the appropriate height, thus simulating the assumption of SDMDs that a thinned stand will have similar attributes and will grow in a similar manner as an unthinned stand that had grown to the same height and density without thinning. Pre-thinning densities were chosen to represent an extreme range of thinning intensities, with basal area removals ranging from 20% to 60%. These and a few other TASS runs are the basis for the yield and treatment assumptions within this report.

4.0 Plotting stand trajectories and thinnings

Plotting an existing stand on a SDMD requires values for number of trees per hectare, top height and quadratic mean diameter. Any two of these parameters can be used to locate the stand on a diagram, although it is usually wise to use all three to confirm that the stand conforms to the inherent relationships within the diagram. There are three possible pairings of the three stand parameters, making possible three distinct points on the diagram. Ideally, the three points will fall within a very close vicinity.

When starting a crop plan from year zero, there is a period of growth that is not represented on the diagrams. This can be a period in which a considerable amount of mortality can occur. The difference between the establishment density and the density at the lowest height represented on the diagrams will therefore have to be estimated.

In general, stands grow upward through the diagram, accumulating height and diameter as they proceed. The TASS-predicted mortality curves serve as a guide for plotting stand trajectories through the diagram. These curves reflect the growth of fully stocked research plots with minimal incidence of pests, and represent the maximum levels of survival that will be experienced under operational conditions. Under most operational conditions, the curves should act as a useful guide for tracking a stand through the diagram. Deviating from these curves should only be considered where tree-killing agents other than intra-specific competition are expected (see section 7.0).

The first step in plotting a crop plan is to define a target stand, based on the stand management objectives. Target stands can be determined based on combinations of several criteria. For final harvest, these may include but are not restricted to culmination of MAI (Table 1), a critical time with either maximum volume or a target piece size for wood delivery to a processing plant, or earliest delivery of wood either of a minimally operable stand volume or a minimally acceptable average piece size. For intermediate entries they might include a critical time for delivery of fiber to a processing facility, the achievement of a minimally operable volume or average piece size, the maintenance of maximum volume production, ensuring stand stability after thinning or ensuring release response by maintaining suitable live crown ratios. The choice of which of these criteria is most critical for a particular stand will depend on the stand's contribution to the achievement of forest level objectives.

Six different crop plan examples are plotted in Figure 4, illustrating some classic even-aged crop scenarios.

Planning thinning regimes is one of the most useful applications of a SDMD. The diagrams can be used to determine the timing and intensity of thinnings in order to achieve set objectives. They can also be used to compare and choose from among a set of potential crop plans. A thinning is simulated by following parallel to a height line from the pre-thinning density to the post-thinning density. This action will result in an unchanged top height but an increased quadratic mean diameter, an effect that is consistent with low thinning. Subsequent growth of the thinned stand is assumed to follow a track similar to a stand that had grown to the same point in the diagram without thinning (see section 4.0).

The optimum timing and intensity of thinnings is based on stand objectives and is determined using various lines and zones within the diagrams. The crown closure line is an important indicator of diameter growth, the range of densities for maximizing CAI is important for maximizing volume production, while the lower limit of the ZICM is an important indicator of stand self-thinning, a phenomenon which should be avoided after the first entry of a commercial thinning regime.

Where volume production is the primary concern, stands should be managed to stay within or as close as possible to the density range for maximizing CAI. This strategy, illustrated in scenario 5 of Figure 4, utilizes frequent light thinnings which maintain a high level of site occupancy while harvesting only those trees which are likely to die before the subsequent thinning entry. This strategy is followed in some parts of Europe, and is used to increase merchantable yields from a stand by as much as 25%. Given current economic conditions in B.C., it is unlikely that such light thinnings can be made to pay for themselves, and heavier thinnings that are financially justified may result in unoccupied growing space which will negate yield gains made by "capturing mortality".

The first entry of a commercial thinning regime should be made at or near the top of the zone of maximum CAI, regardless of the position of the lower limit of the ZICM. While this will maximize volume production, height/diameter ratios should be monitored for stand stability after thinning and live crown ratios should be assessed to ensure adequate crown volumes for a thinning response. Subsequent entries should be dictated by the point at which a stand trajectory intersects the lower limit of the

Table 1. Culmination of Mean Annual Increment (MAI) for managed stands of lodgepole pine, interior Douglas-fir and white spruce at four site indices and seven establishment densities as predicted by the TASS growth model. Age, height and merchantable (dbh > 12.5 cm) MAI are provided.

		Density at Establishment (stems/ha)						
SI_{50}		350	500	700	1000	1500	2500	4500
					Lodgepole pine			
14	Age	119	114	110	106	104	104	104
	Height	21.1	20.8	20.5	20.2	20.0	20.0	20.0
	MAI	1.36	1.72	2.15	2.54	2.86	2.95	2.85
17	Age	101	97	93	84	78	75	74
	Height	23.2	22.8	22.4	21.4	20.8	20.2	20.1
	MAI	2.03	2.53	3.12	3.65	4.06	4.18	4.04
20	Age	85	82	77	73	66	63	62
	Height	24.8	24.5	23.8	23.2	22.0	21.5	21.3
	MAI	2.85	3.53	4.31	4.97	5.45	5.57	5.37
23	Age	93	91	75	62	57	52	52
	Height	29.0	28.8	26.7	24.4	23.4	22.2	22.2
	MAI	3.93	4.75	5.70	6.49	7.03	7.12	6.87
					White spruce			
14	Age	152	142	134	126	124	111	111
	Height	28.8	27.9	27.0	26.1	25.8	24.1	24.1
	MAI	2.43	2.86	3.34	3.70	3.95	3.93	3.84
17	Age	124	118	110	100	99	92	91
	Height	29.4	28.7	27.6	26.1	25.9	24.7	24.5
	MAI	3.11	3.65	4.25	4.67	4.99	4.94	4.83
20	Age	109	99	93	84	80	78	77
	Height	30.9	29.4	28.4	26.7	25.9	25.4	25.2
	MAI	3.91	4.56	5.28	5.77	6.14	6.07	5.93
23	Age	102	89	80	73	67	66	66
	Height	33.2	31.1	29.2	27.6	26.1	25.8	25.8
	MAI	4.87	5.61	6.44	6.99	7.41	7.32	7.14
26	Age	87	85	73	63	57	56	56
	Height	33.9	33.6	30.9	28.2	26.2	25.9	25.9
	MAI	5.99	6.85	7.75	8.34	8.77	8.66	8.45
					Interior Douglas-fir			
14	Age	189	181	171	163	155	154	159
	Height	27.3	26.8	26.3	25.8	25.2	25.2	25.5
	MAI	1.44	1.66	1.87	2.04	2.17	2.18	2.12
17	Age	169	160	151	144	138	138	140
	Height	31.6	31.0	30.2	29.6	29.1	29.1	29.3
	MAI	2.47	2.75	3.01	3.20	3.34	3.36	3.28
20	Age	150	128	121	120	116	116	118
	Height	35.3	33.0	32.1	32.0	31.9	31.5	31.7
	MAI	3.65	3.99	4.32	4.55	4.70	4.71	4.63
23	Age	118	115	115	110	95	94	95
	Height	36.4	36.0	36.0	35.2	32.6	32.4	32.6
	MAI	4.99	5.40	5.75	5.97	6.13	6.14	6.03
26	Age	101	99	92	91	91	91	91
	Height	38.1	37.7	36.2	36.0	36.0	36.0	36.0
	MAI	6.36	6.84	7.25	7.52	7.67	7.65	7.56

ZICM. *Any trees which die due to inter-tree competition after a first commercial thinning entry indicate that the prior entry was too light, as the dead trees could have been harvested previously both to recover their volume and to provide more growing space for the true residual crop trees*. It should be remembered, however, that the lower limit of the ZICM will shift upward on natural stand diagrams after a thinning entry that reduces spatial heterogeneity. The width of the ZICM on the planted stand diagram can be used as a first approximation for the magnitude of the shift.

Thinning regimes in which objectives are for other than maximum volume production will generally use lower densities with a lesser utilization of growing space. Maximum diameter growth, for example, is achieved when a stand is grown for a long period of time below the crown closure line. Such a regime will have large volume penalties, and will result in long live crowns with coarse branches. An intermediate regime with smaller volume penalties but still dictated by a target quadratic mean diameter can be planned by determining the points at which the target diameter line intersects various heights. The heights can be translated into harvest ages through the use of site index curves. Other stand targets may be expressed in terms of basal area or, particularly in regimes incorporating integrated resource management objectives, percent crown cover (see section 8.0).

When first plotting a crop plan, a choice must be made whether to use the natural stand or planted stand diagram for a particular species. This decision should be based more on the current or expected spatial distribution within a stand than on the actual stand origin. Likewise, if the spatial distribution is changed through pre-commercial thinning, it may be appropriate to switch a trajectory from a natural stand diagram to a planted stand diagram, as the rates of mortality in the thinned stand will follow more closely to the planted condition. Changes from a natural stand diagram to a planted stand diagram are less appropriate under commercial thinning scenarios.

Only uniform low thinnings should be plotted using these SDMDs. While deviations from the fixed density/height/diameter relationships inherent in the diagrams are reasonably small and predictable following a low thinning, other thinning strategies may result in much larger deviations such that the predictions of the diagram become virtually useless. This will be particularly true of crown or selection (Smith 1986) thinning.

5.0 Making yield estimations

Stand density management diagrams and other average-stand level models are much less sophisticated predictors of yield than are more flexible models such as TASS, which is capable of tracking many attributes of every tree in a stand. Having stated this, it can be recognized that first approximations of yield are possible with SDMDs, and are useful to obtain feasibility estimates for commercial thinnings, or to evaluate the relative merits of a number of options for a crop plan. In doing so, it is useful to understand the predictive shortcomings of the diagrams.

Total yields can be calculated for any point on the diagram by multiplying mean tree volume by stand density (Figure 5). Care must be taken in reading these values from the x- and y-axes, as small errors in readings from the logarithmic scales can result in considerable differences in the final calculation, *particularly in the upper portions of the diagrams where most yield calculations will be made*. For example, a stand with a mean tree volume of 0.95 m^3 and a density of 550 trees per hectare would have a total volume of 522.5 m^3/ha. If both of these values are underestimated by two tick marks on their respective axes, the answer comes out at 492.9 m^3/ha, a difference of almost 30 m^3/ha. The potential for errors such as these have been minimized on these diagrams through the provision of grid lines and finely graded tick marks on the axes.

Merchantable yields can be estimated by applying a correction factor to total yield. This factor will vary by average stand diameter and height and hence is expressed as a function of volume. Values for converting total volume to merchantable volume can be found in Figure 6. A further deduction can be made to get to operational yields by deducting from the yield prediction an amount equivalent to the percentage of the land area that is non-productive, such as rock, water or unstocked gaps. Further information on the application of operational adjustment factors is available in the WinTIPSY manual (Mitchell et al. 1995)

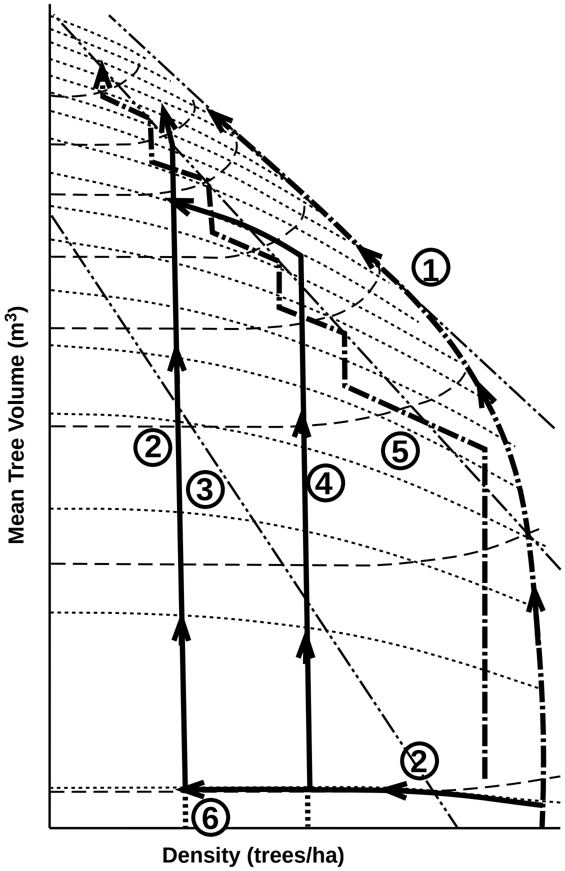

Figure 4. Classic options for forest crops that can be planned and compared on a SDMD include dense natural regeneration carried through to rotation for high total volume production at low cost (1), pre-commercial thinning of dense natural regeneration to a final crop density (2), thinning to final crop density coupled with pruning to increase product values (3), pre-commercial thinning to a density which allows for a single commercial thinning (4), and establishing moderately dense stands followed by frequent light commercial thinnings to maximize volume production (5). Establishment can also be by planting to the desired density rather than through pre-commercial thinning natural stands (6).

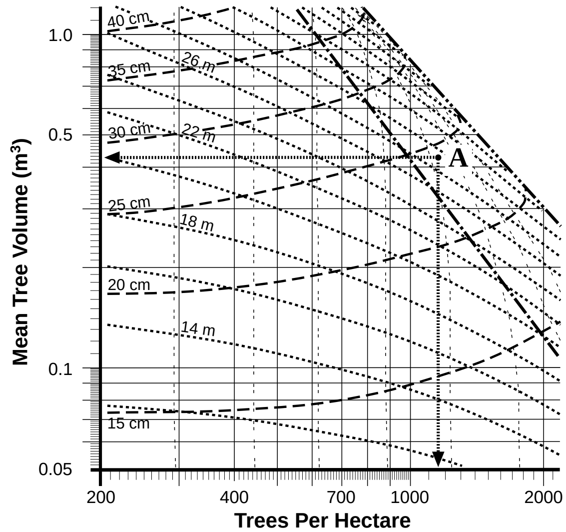

Figure 5. Volume calculation: total stand volume at point A is calculated by multiplying mean tree volume by trees per hectare: 1160 stems/ha × 0.425 m^3/tree = 493 m^3/ha

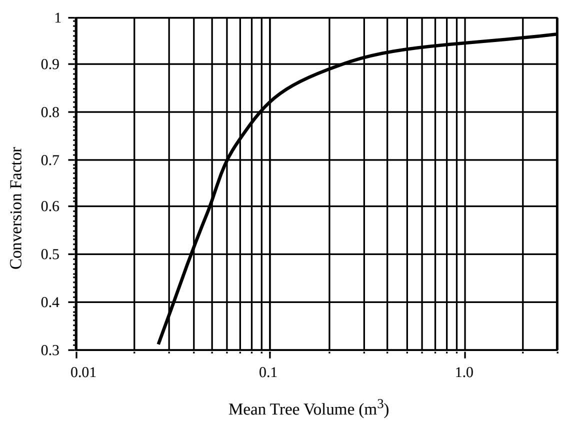

Figure 6. Conversion of total volume to merchantable volume: total volume can be converted to merchantable volume (assuming a merchantability limit of 12.5 cm dbh) by multiplying by the conversion factor above. This generalized relationship will slightly (<5%) overestimate merchantable yields from higher density stands. The graph was plotted based on output from the WinTIPSY program.

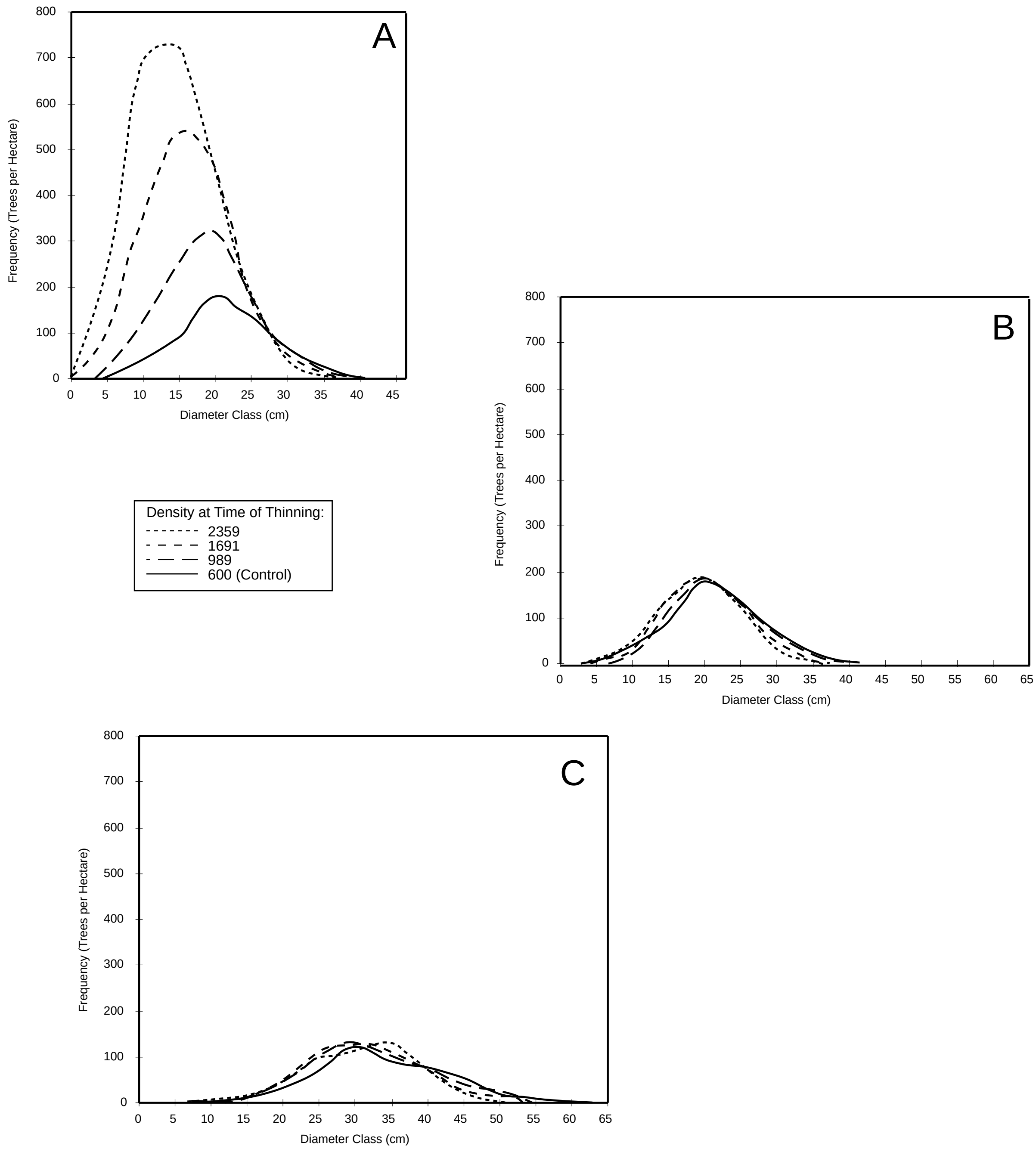

Figure 7. Stand density management diagrams assume that a thinned stand will look and behave the same as an unthinned stand grown to the same density without thinning. Here that assumption is tested with three white spruce stands at different densities but the same top height (A) thinned at 18 m to 600 trees per hectare. After thinning (B), their diameter distributions are very similar to the low density unthinned stand (control), but with lower ranges and means. When grown to 28 m top height (C), the diameter distributions are still of similar shape. Immediately after thinning, the quadratic mean diameter of the thinned stands ranged from 0.5 cm to 2.0 cm less than the low density unthinned stand. At 28 m, the disparity had increased to 1.0 to 3.0 cm. The greatest disparity was for the heaviest thinning, the least for the lightest thinning. The stands in this example were modeled using TASS. Thinning assumed priority removal of the smallest trees with some spatial constraints.

The prediction of yields at the end of commercial thinning regimes is complicated by the assumption that thinned stands will look and behave the same as a stand that had grown to the same height and density without thinning. Figures 7 and 8 illustrate the differences between the pre-and post-thinning diameter and height distributions of three thinned stands, and that of an unthinned stand grown to the same density as the thinned stands at the same height. The thinned stands have a lower quadratic mean diameter, a higher average height and different diameter and height distributions. The magnitude of this difference will be small in a pre-commercial thinning regime, but will be greater in commercial thinnings, with heavier and later thinnings having larger impacts. When these stands are allowed to develop over time, there are small differences in the rates of mortality, but the differences in the height and diameter distributions remain constant. The overall result is that the SDMDs overestimate quadratic mean diameter at final harvest but in heavier thinnings will underestimate total yield. The effect on merchantable yield will depend on quadratic mean diameter at the time of harvest. The quadratic mean diameter may be overestimated by as much as 4 cm in very heavy thinnings.

Thinning yields can be estimated on the diagrams by subtracting the volume (trees per hectare x mean tree volume) of the post-thinning stand from that of the pre-thinning stand. This exercise again assumes that

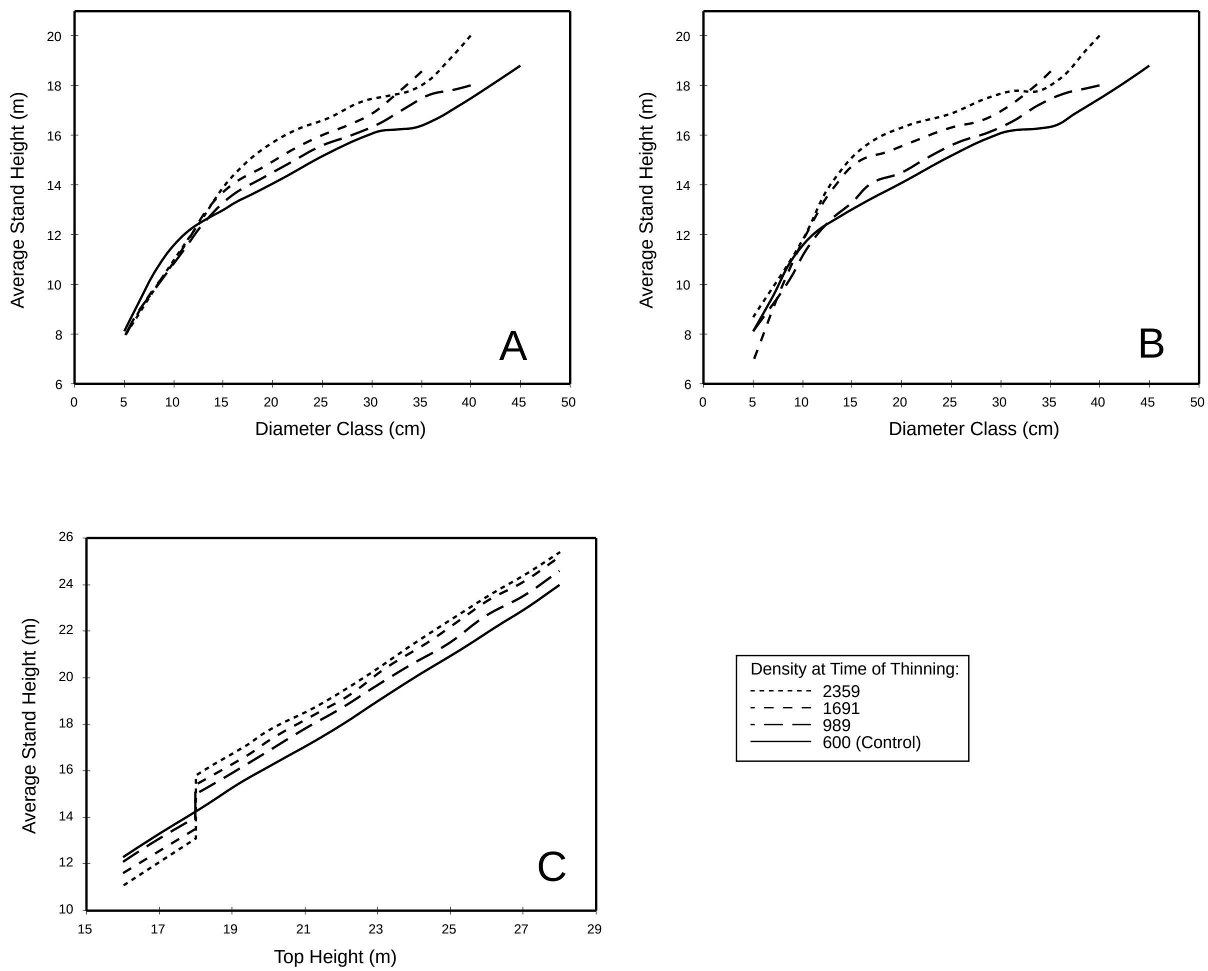

Figure 8. The height distribution by diameter class is altered by a low thinning (as modelled by TASS). From the pre-thinning (A) to the post-thinning (B) distributions, average heights are raised in the lower diameter classes where shorter, poorer stems are preferentially removed. Dense stands have a lower average height prior to thinning, but a larger average height after. The magnitude of the average stand height increase varies with thinning intensity, with the greatest effect in the heaviest thinnings. In all thinned stands, the average height will be greater than an unthinned low density stand of the same top height (C), and the absolute increase in average height relative to an unthinned stand is maintained over time as the stands continue to grow.

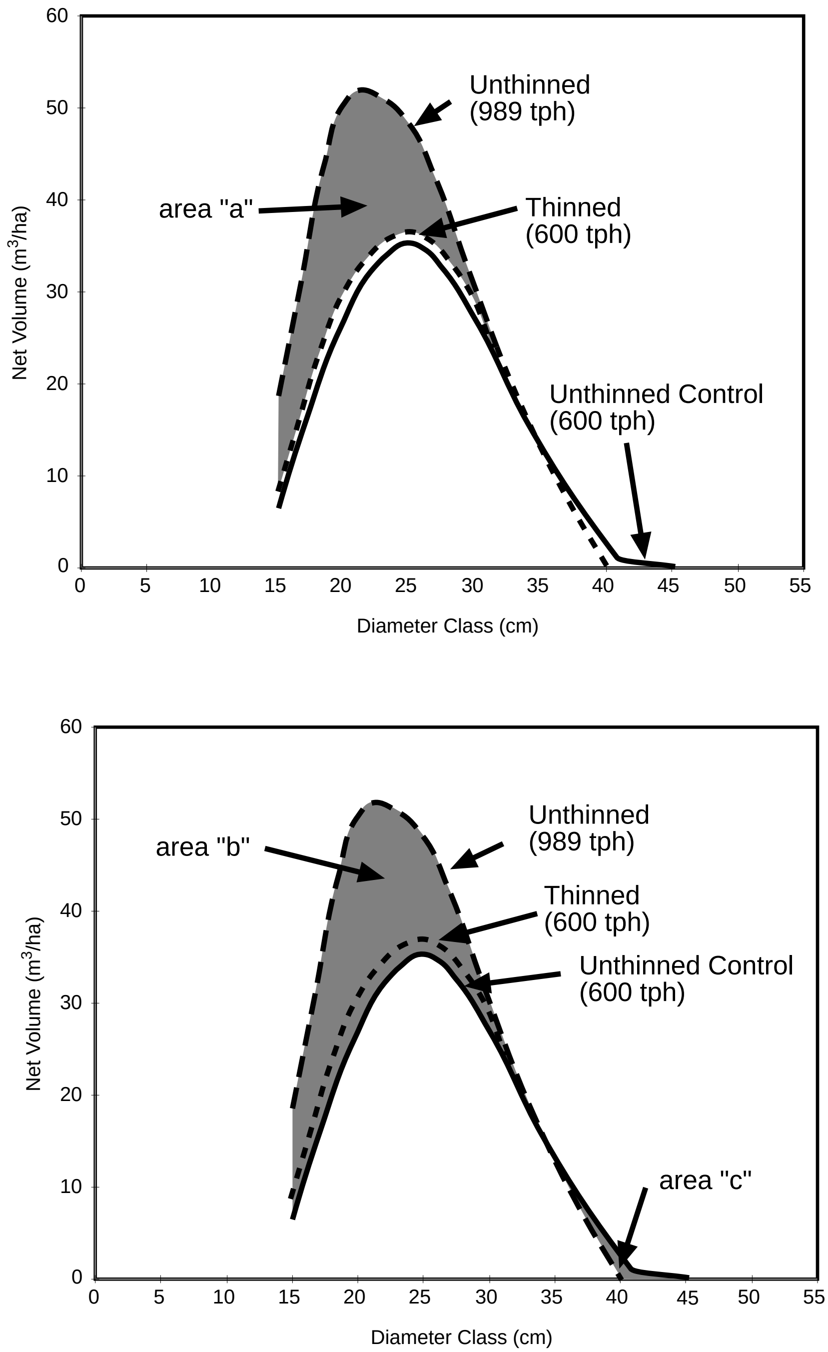

Figure 9. Assumptions in calculating thinning volumes: in the volume distribution by diameter class curves above, the volume removed in a thinning is the difference between the area under the unthinned stand curve and the area under the thinned stand curve (area "a"). Using a SDMD, the thinned stand curve is replaced by an unthinned stand curve of the same density, where the predicted thinning volume is again the difference of the areas under the curves (area "b" - area "c"). The error in the prediction of thinning volumes depends on the balance between the band of area represent by "b" - "a" and the area of "c". In very light and early thinnings, the area "c" is small, and the stand density management diagram will slightly overestimate thinning volumes. In heavier late thinnings, the area of "c" becomes much larger, resulting in large (up to 20%) underestimations of thinning volumes.

the post-thinning diameter distribution (and the resulting volume by diameter class) of a high density stand is identical to that of an low density stand which grew to the same point in the diagram (Figure 9). The difference between the diameter distributions of the high density and low density stands would then reflect the stems that are available for removal. This assumption is more valid for light thinning entries than for heavier ones, but is never perfect. The SDMD will provide reasonable estimates of thinning volumes for light and early thinnings, but will underestimate yield for heavy late thinnings. Converting to merchantable yields for thinnings is difficult, as quadratic mean diameter and mean tree volume for the thinnings cannot be derived directly from the diagrams.

Improved yield predictions can be achieved using the WinTIPSY software program for regimes that do not include commercial thinning. This program will also provide a more detailed stand description within its managed stand yield tables than is available from the SDMDs. For commercial thinning regimes, the only option currently available for improved yield precision is customized TASS runs. These are available through the B.C. Ministry of Forests, Forest Productivity and Decision Support Section[3].

[3] The current phone number is (604) 387-6948.

6.0 Case studies

Two case studies are provided to illustrate how the diagrams can be used in making decisions related to density management.

Case Study #1 - Accelerating Operability

Suppose that you have a temporary wood supply shortage projected for a period 40 years in the future. You have three dense, naturally regenerated 10-year-old lodgepole pine stands with site indices of 13 m, 16 m and 19 m. You wish to thin these stands in order to achieve operable stand conditions at the time of the shortfall. You need to reduce densities such that diameter growth is increased, but at the same time you wish to minimize the sacrifice in volume production. What density should you thin to? What are the volume sacrifices?

Assuming a minimum operable stand has a quadratic mean diameter of 20 cm:

1. Highlight the 20 cm diameter line on the planted stand lodgepole pine diagram (Figure 10).
2. Use site index curves to determine the expected height of each of the stands at the target harvest age. Don't forget to convert total age to breast height age when using the site index diagram. For the three stands in this example, the heights at age 50 will be 11 m, 14 m and 17 m respectively.
3. Plot the intersection of the respective height lines with the minimum operability diameter. By drawing a vertical line from these points to the X-axis, the maximum density at which your target stand diameter will be achieved can be determined. Thinning to this density will achieve your operability target while minimizing the sacrifice in volume production. In this example, the SI_{50} 16 m and 19 m stands should be thinned to 850 and 1250 stems/ha respectively. There is no intersection for the lower site index stand, *therefore the target diameter cannot be achieved for this stand at any density*. Consequently, this stand should not be thinned with the objective of harvesting it at age 50.

Harvest volumes for the site index 16 m and 19 m stands can be calculated and compared to the potential for volume production on the sites (Table 2). There was a sacrifice of 1.3 m^3/ha/yr on the medium site and 0.9 m^3/ha/yr on the better site.

Case Study #2 - Determining Commercial Thinning Residual Densities

A natural white spruce stand with a site index of 20 m has been proposed as a candidate for commercial thinning. The current stand age is 60 years, the top height is 20 m, and the current density is 2500 trees/ha. The final harvest is expected to occur at or near culmination of MAI. What density should these stands be thinned to? What will the thinning volume be?

1. The first step is to determine the culmination age and height for the thinned stand. From Table 1, we can determine that the unthinned stand would have a culmination age of approximately 78 years. Given the dense condition of the stand at present, we can assume that the thinning will be a heavy removal, and that the rotation will be

Table 2. Calculating volumes and mean annual increments for two stands in a pre-commercial thinning regime.

Site Index (ref.age 50)	Total Volume[1] m^3/ha	Total to Merch.[2] Vol. Conversion	Merch. Volume m^3/ha	MAI[3] m^3/ha·yr at early harvest age	MAI[4] at Culmination Age
16	121	0.86	104	2.1	3.4
19	219	0.87	190	3.8	4.7

1. Mean tree volume × Density
2. From Figure 6
3. Merchantable volume ÷ Age
4. Interpolated from Table 1.

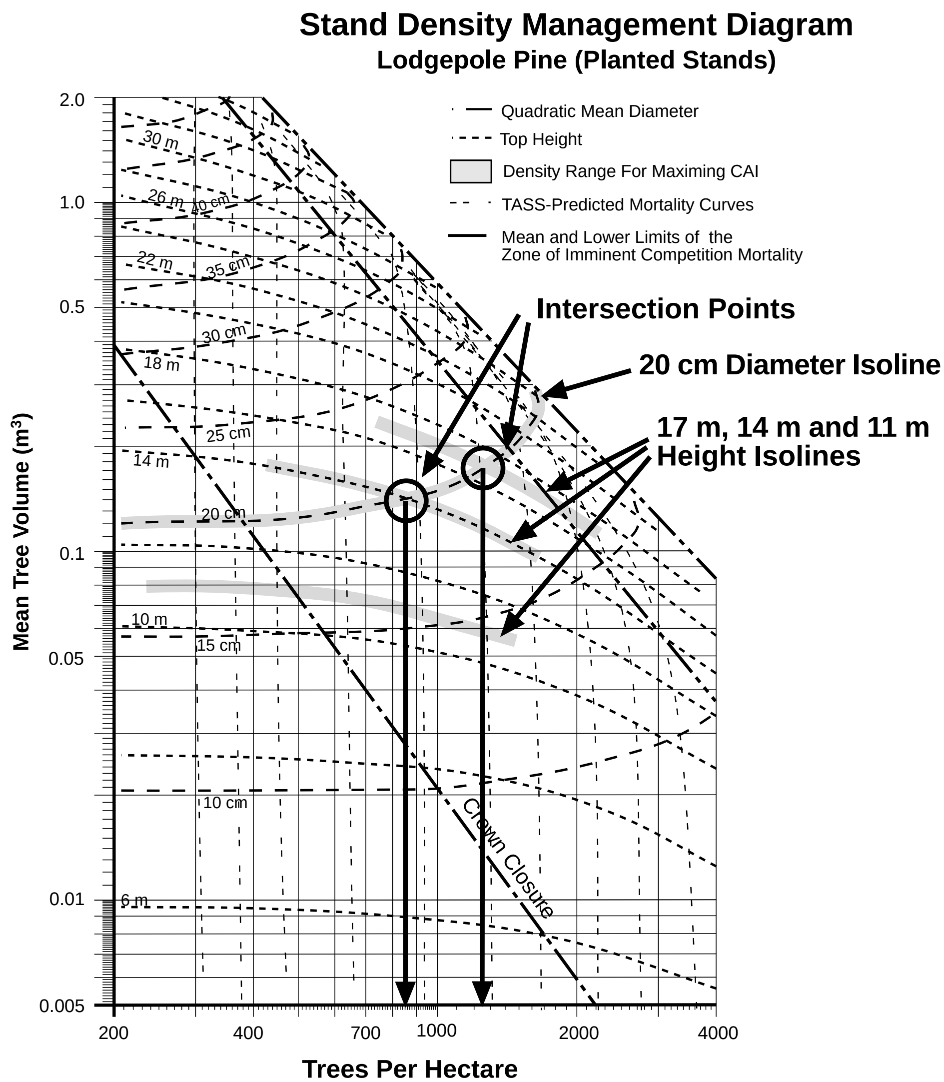

Figure 10. Application of the SDMD to determine post-thinning densities with the objective of reaching a minimum operability standard (20 cm average stand diameter) at a given age (50 years) with three different stands of SI_{50} 13, 16 and 19. The high site will be thinned to 1250 stems/ha, and the medium site to 850 stems/ha. The low site cannot reach the stated objective in the given time.

lengthened by approximately 20%[4]. The new culmination age for the thinned stand will therefore be be 92 years. Using the site index curves for white spruce, the height for an SI_{50}=20 white spruce stand at 92 years is 28 m.

2. Given the decrease in stand heterogeneity, the lower limit of the ZICM must be raised, using the position of the same line on the planted stand diagram as a guide (see Figure 11). The 28 m height line on the diagram intersects the new lower limit of the ZICM at 650 trees per hectare. As we expect to experience only a very small amount of mortality in our thinned stand (as compared to an unthinned natural stand at the same density), we will accept this figure as our post-thinning density.

3. The thinning volume can be calculated by subtracting the thinned stand volume from the unthinned stand volume:

2500 trees/ha × 0.145 m^3/tree	362 m^3/ha
650 trees/ha × 0.30 m^3/tree	- 195 m^3/ha
	167 m^3/ha

This is a heavy thinning and the thinning volume will be underestimated by 10-20% (see Figure 9). Given this, an intermediate thinning could be contemplated in order to maintain a higher level of site occupancy and to avoid problems with destabilization of the stand due to excessive opening.

[4] In nine single-entry commercial thinning regimes for each of three species simulated using TASS, the culmination age was increased by thinning by as little as 5% for very light thinnings to as much as 25% for very heavy thinnings.

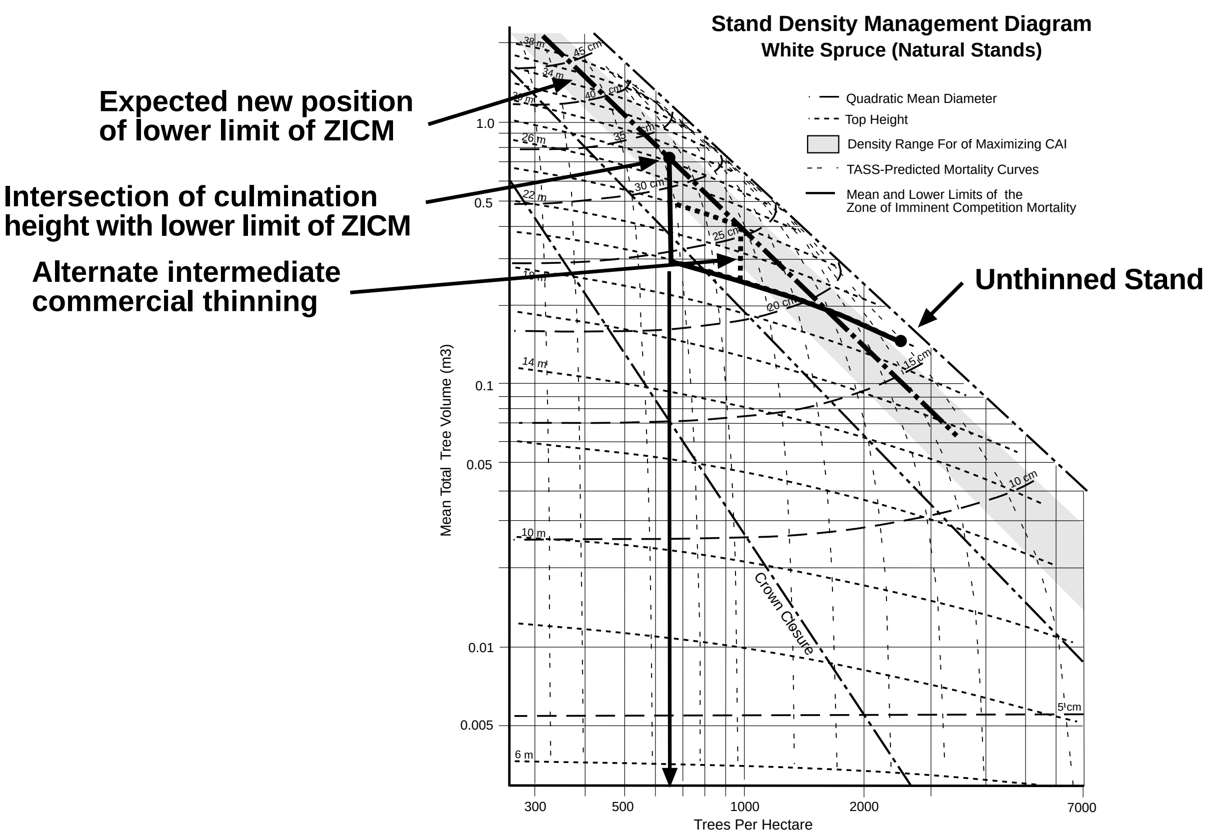

Figure 11. Application of the stand density management diagram to determine a post-thinning density where the objective is a final harvest at culmination age. The lower limit of the ZICM is shifted upward to reflect the decreased mortality resulting from the post-thinning homogenization of the stand. The density at which the stand will intersect the lower limit of the ZICM at culmination age (650 stems/ha) is determined as the post-thinning density. An alternate intermediate thinning is suggested to prevent loss of volume growth due to lack of growing space occupation.

7.0 Dealing with pests

Pests can be split into three categories depending on their impact on stand dynamics. Pests that kill trees in distinct groups, such as root rots, have catastrophic effects within a limited area of influence, but have no effect on the remainder of the stand. The influence of these pests is best dealt with by netting down the stand area, but not affecting growth patterns in the rest of the stand. Pests which kill trees randomly throughout the stand, such as stem rusts, should be treated as natural thinning agents. In this case, a more rapid rate of mortality than that suggested by the TASS-generated mortality curves should be assumed. As predicting the mortality effects of pests is very difficult, a “best guess” for the slope of the mortality curve will be required. Local experience will likely be the best guide. For pests that affect tree growth rates but do not affect mortality, the effects on growth can be simulated by using a lower site index curve. Once again, the magnitude of the pest effect is best determined through local experience. Pest experts in the B.C. Ministry of Forests Regional Offices may also be of help.

8.0 Adding additional parameters to the diagrams

Stand parameters other than quadratic mean diameter and height can be plotted on SDMDs as isolines. Usually, they are not plotted initially either because the base data is not available or because the diagrams would become overly cluttered.

Stand basal area can be plotted on the diagrams using information that is already available. For each 5-cm isoline of quadratic mean diameter, the mean tree basal area can be calculated using the formula for a circle (πr^2). Dividing this value into a range of stand basal area values (5-m^2 increments, for example) will provide the stand densities at which the target stand basal areas are achieved for the given quadratic mean diameter. If these points are plotted on the given diameter isoline, and the exercise is repeated for a range of diameter isolines, the respective points for a given stand basal area can be joined up to provide a set of basal area isolines.

Percent crown cover can also be added to the diagrams as a series of isolines. This stand attribute is important for making evaluations of stand value for resources such as wildlife habitat, livestock grazing, snow interception and hydrologic storage, and recreation. Plots of percent crown cover for the six diagrams covered by this report are available in Appendix III.

Both of the stand attributes listed above are sensitive to thinning, and both will be overestimated by the diagrams after a thinning. The later and heavier the thinning, the greater will be the impact. If an SDMD overestimates quadratic mean diameter by 2 cm, the basal area will be overestimated by 3.6 m^2/ha at a quadratic mean diameter of 18 cm, and by 6.4 m^2/ha at a quadratic mean diameter of 30 cm. Percent crown cover will be overestimated immediately after a thinning, but will recover as crowns re-occupy the growing space.

9.0 A final caution

It is important to recognize that SDMDs, like most other growth models, simulate the average growth pattern of a wide variety of potential growth trajectories. Given a starting condition, many possible future outcomes may be possible; there is no “right” answer to the question “What will this stand look like 50 years from now?”. In Figure 2B, trajectories typical of a large number of permanent sample plots are shown, illustrating the differences that can occur. We cannot currently provide adequate explanations for why stands differ to this degree; we know many of the influences but not their degree of influence or how they interact. The best we can do, therefore, is to plan based on the average condition, and either test for or be aware of the range of outcomes which may happen. Ongoing monitoring of treated stands is required to determine whether projections for future treatments are still accurate or appropriate.

10.0 Summary

Stand density management diagrams are useful tools for forest crop planning. In particular, they can be used to determine appropriate density regimes for achieving set management objectives. They provide a tool for answering questions such as “What density should I thin to?” given a specified stand management objective. Furthermore, the diagrams are also useful tools for gaining an understanding of stand dynamics and the implications of various density manipulations on the realization of management objectives.

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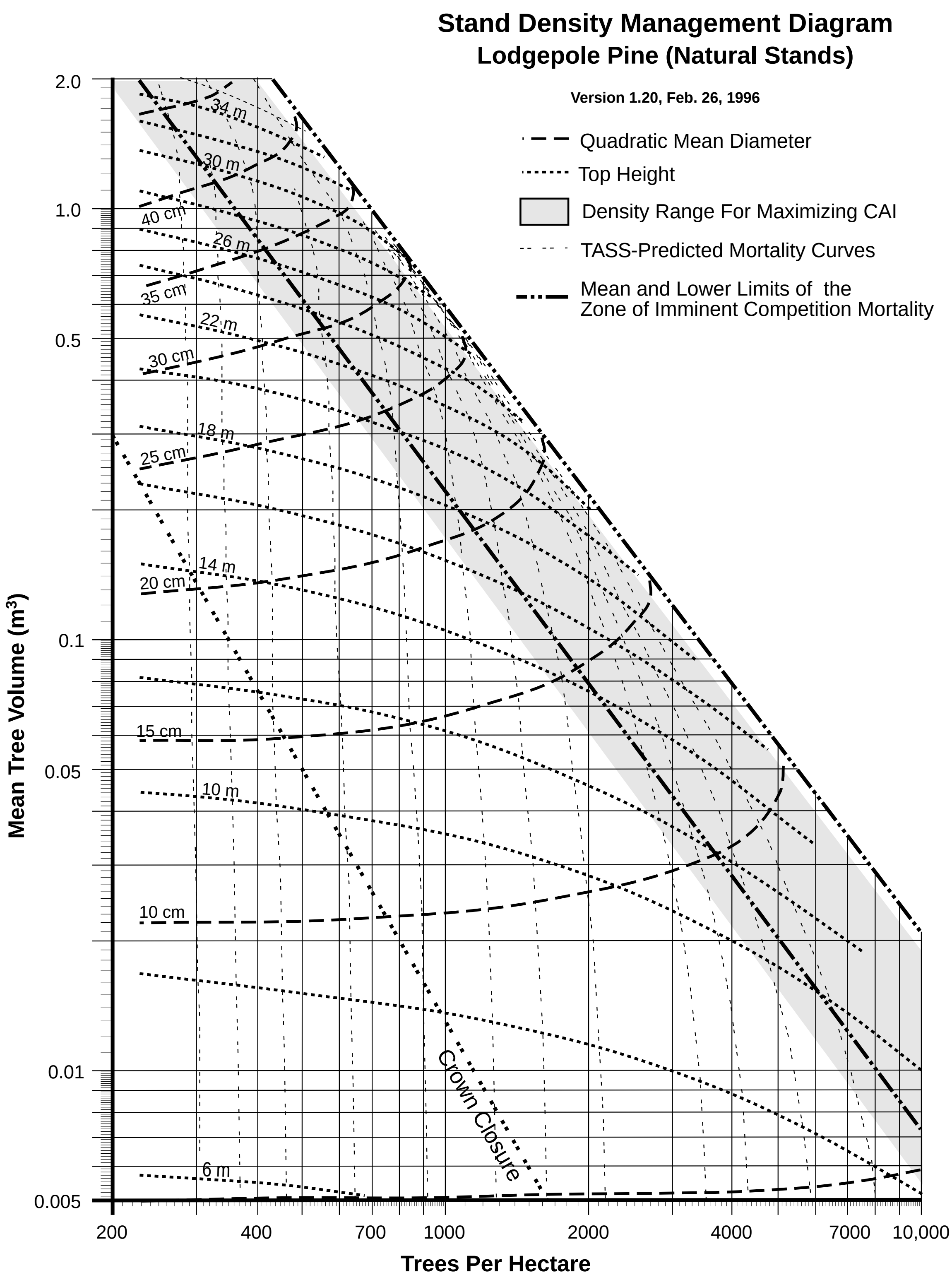
Appendix I

Stand density management diagrams for lodgepole pine, white spruce, and interior Douglas-fir



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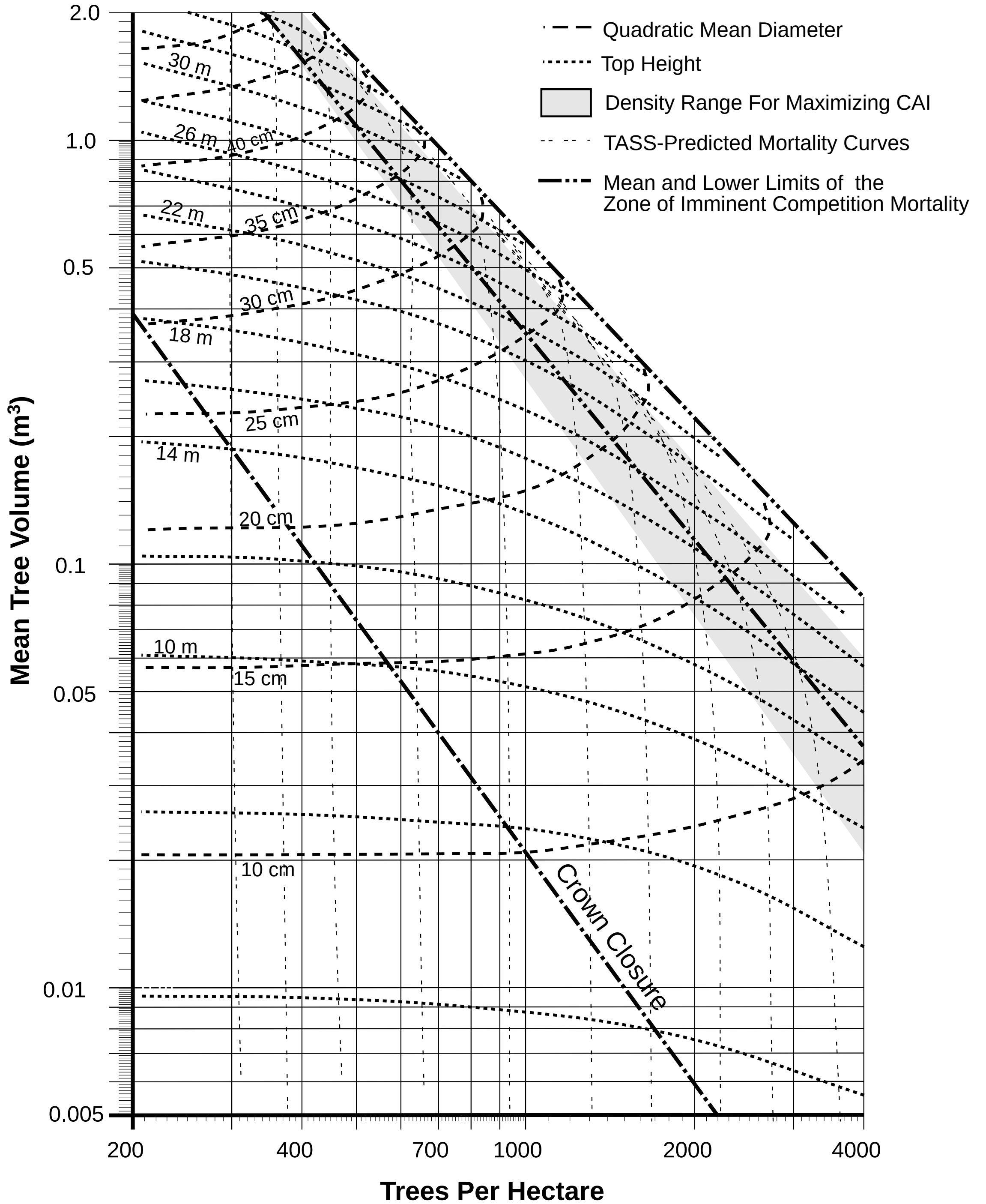
Canadian Forest Service
Pacific Forestry Centre

Data Source: TASS-generated managed stand yield tables contained in the computer program WINTIPSY (British Columbia Ministry of Forests, Forest Productivity and Decision Support Section)

Stand Density Management Diagram
Lodgepole Pine (Planted Stands)

Version 1.20, Feb. 26, 1996



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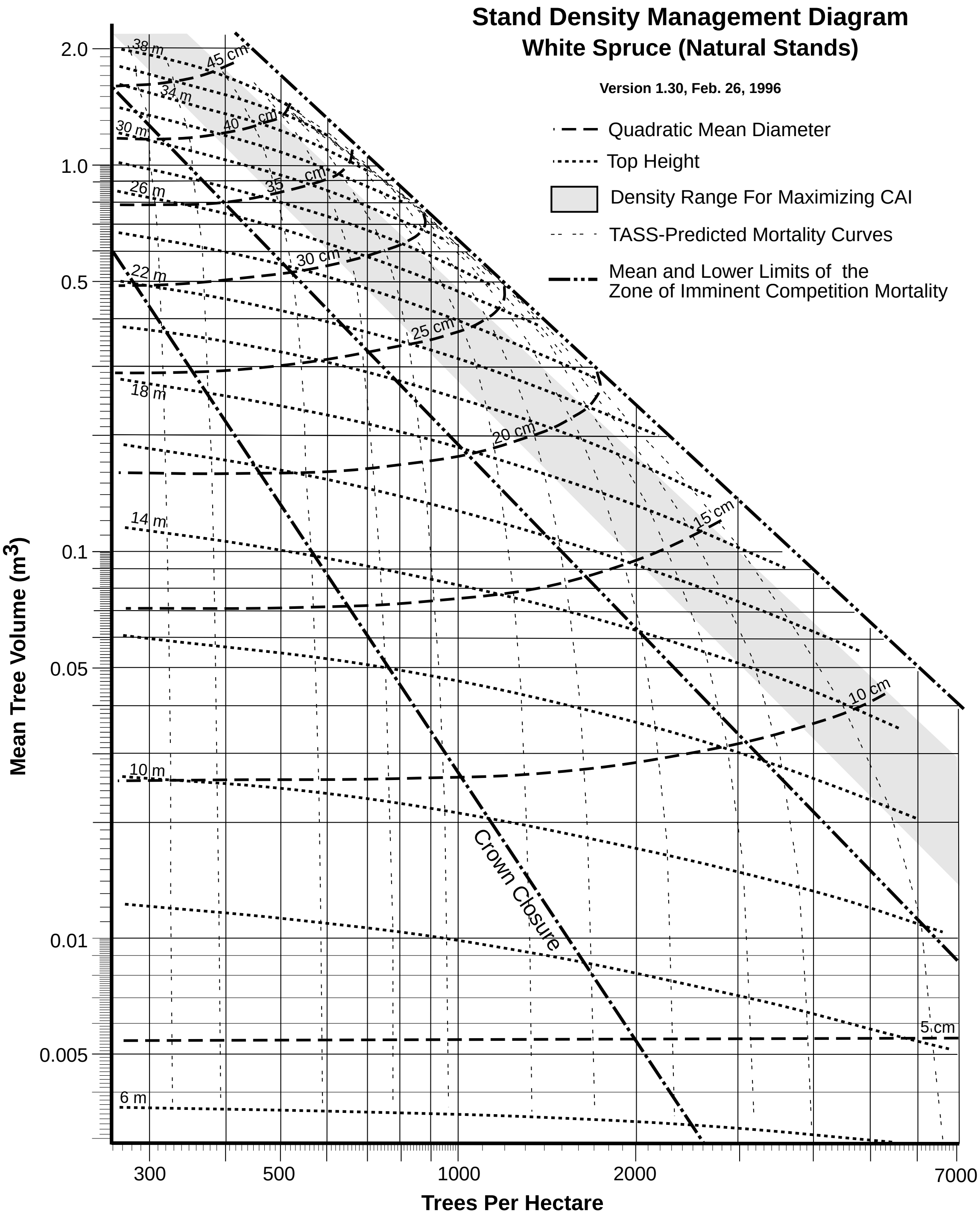

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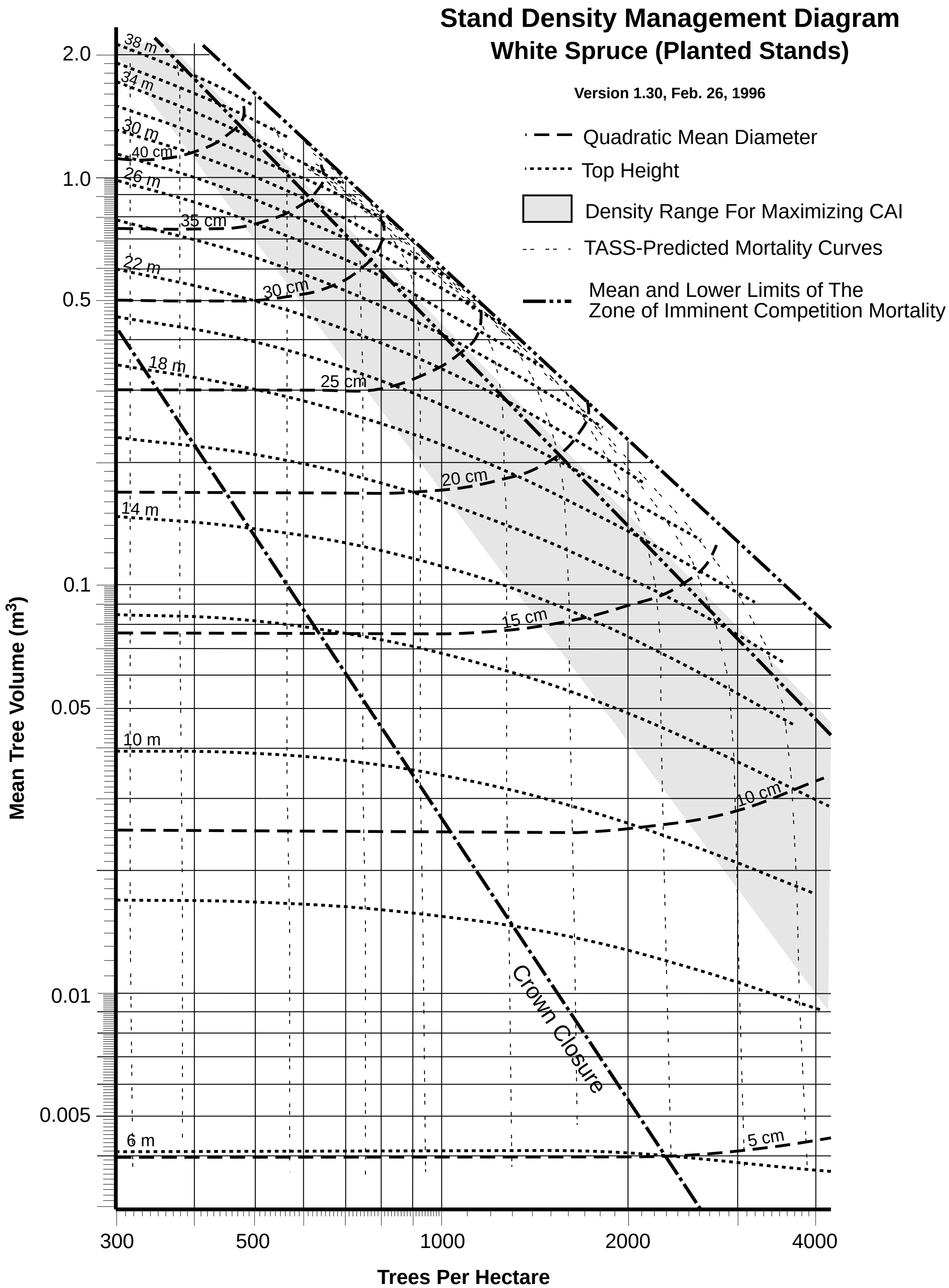

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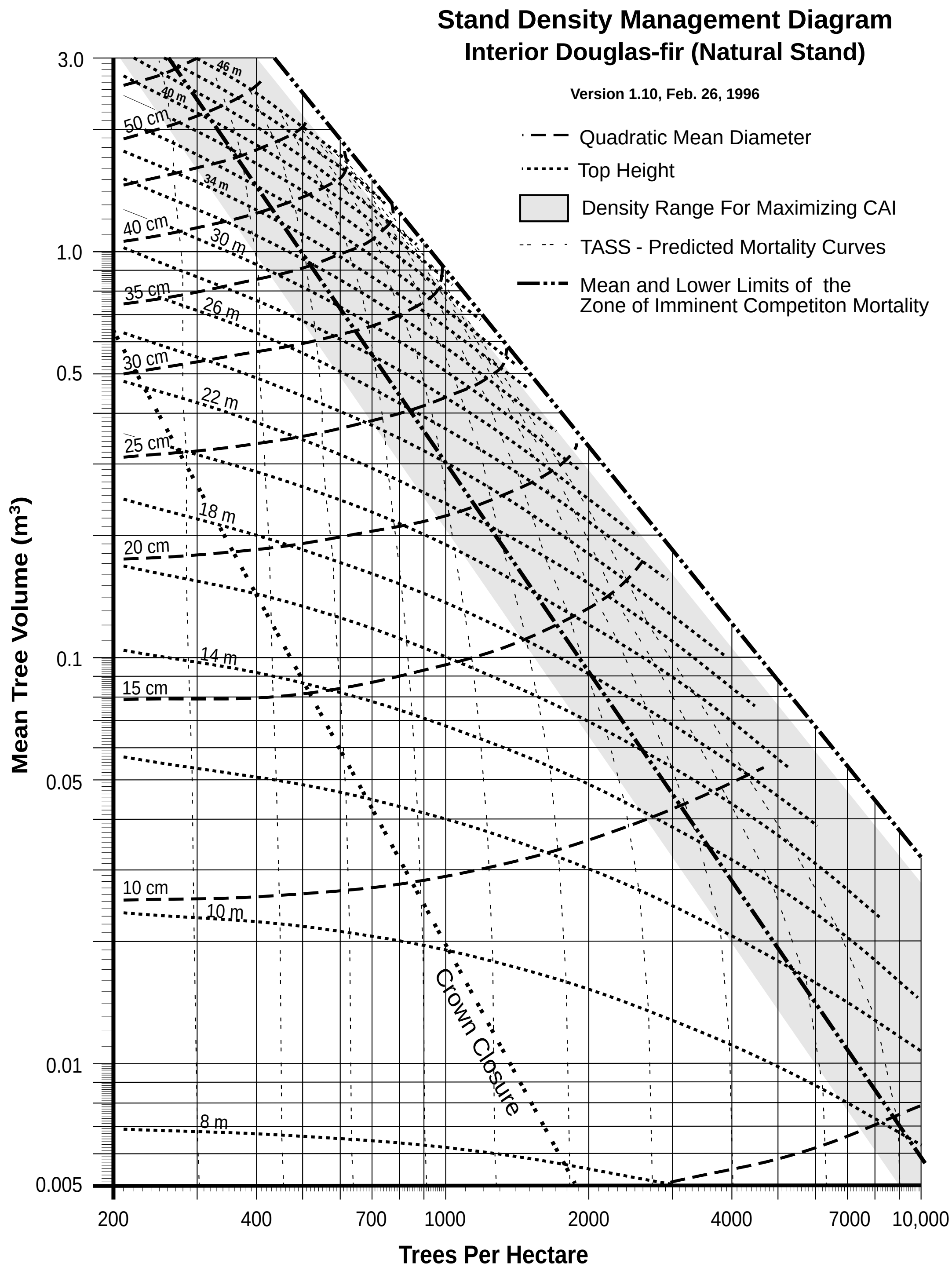

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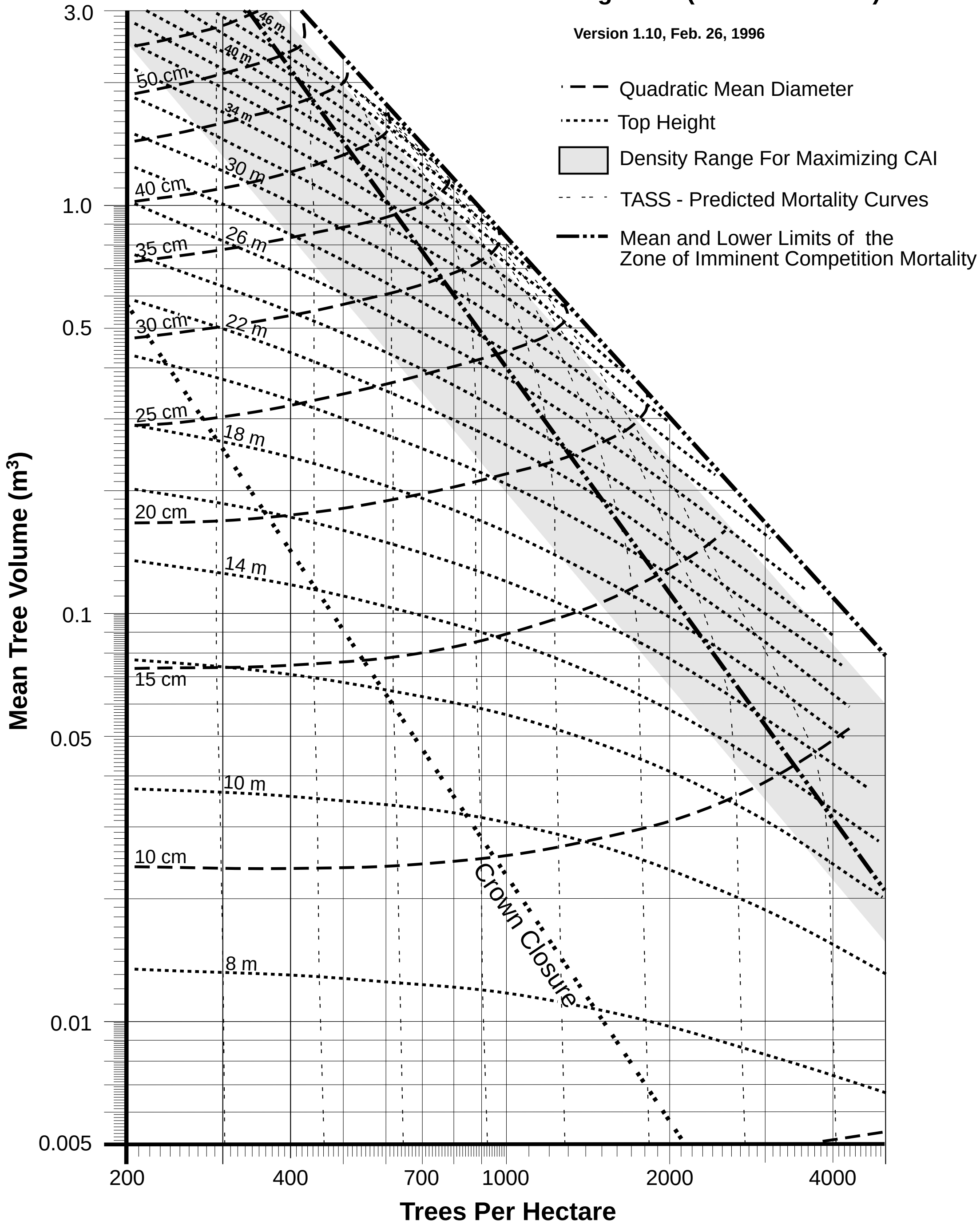
Data Source: TASS-generated managed stand yield tables contained in the computer program WINTIPSY (British Columbia Ministry of Forests, Forest Productivity and Decision Support Section)

Stand Density Management Diagram
Interior Douglas-fir (Planted Stands)



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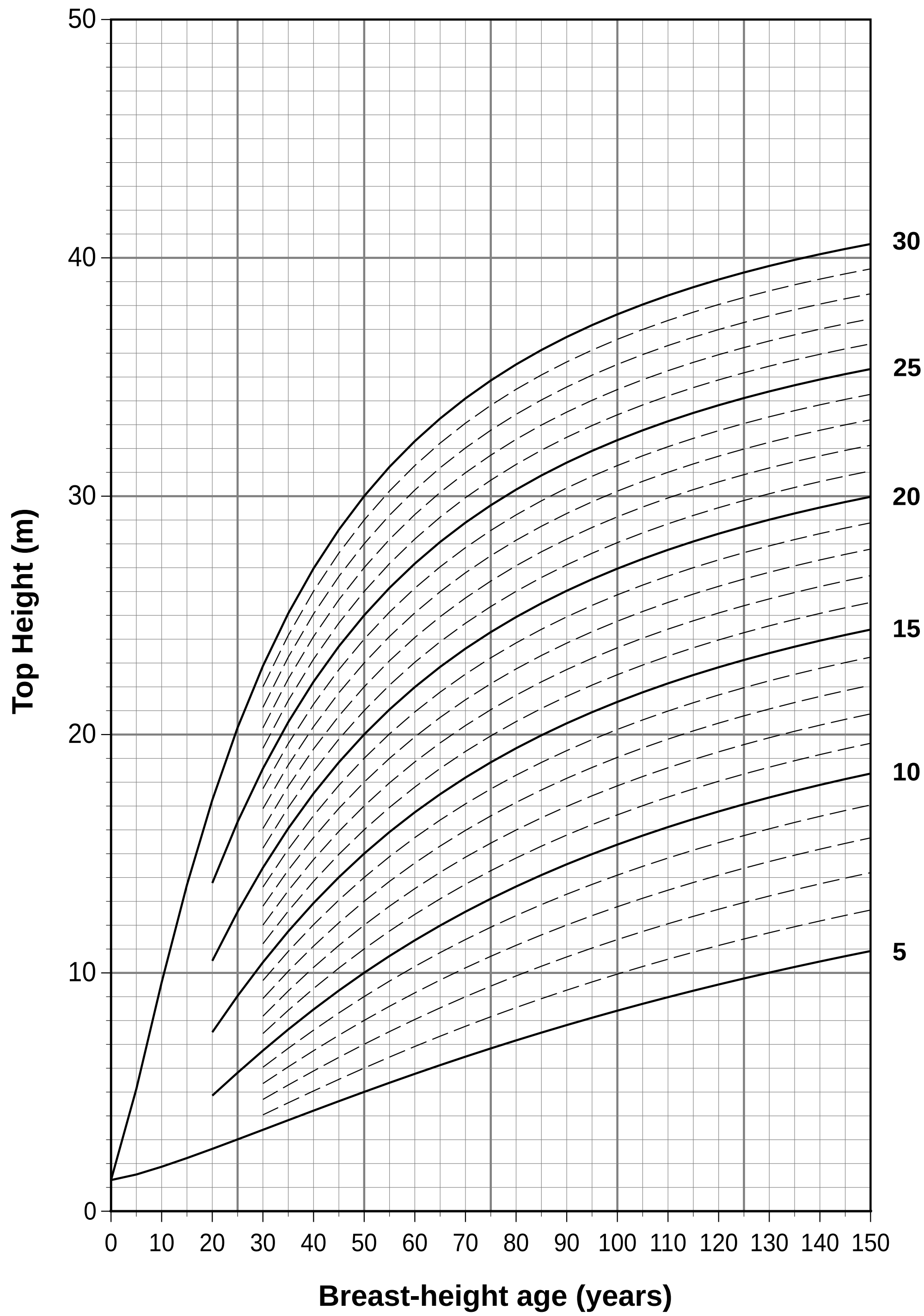
Data Source: TASS-generated managed stand yield tables contained in the computer program WINTIPSY (British Columbia Ministry of Forests, Forest Productivity and Decision Support Section)

Appendix II

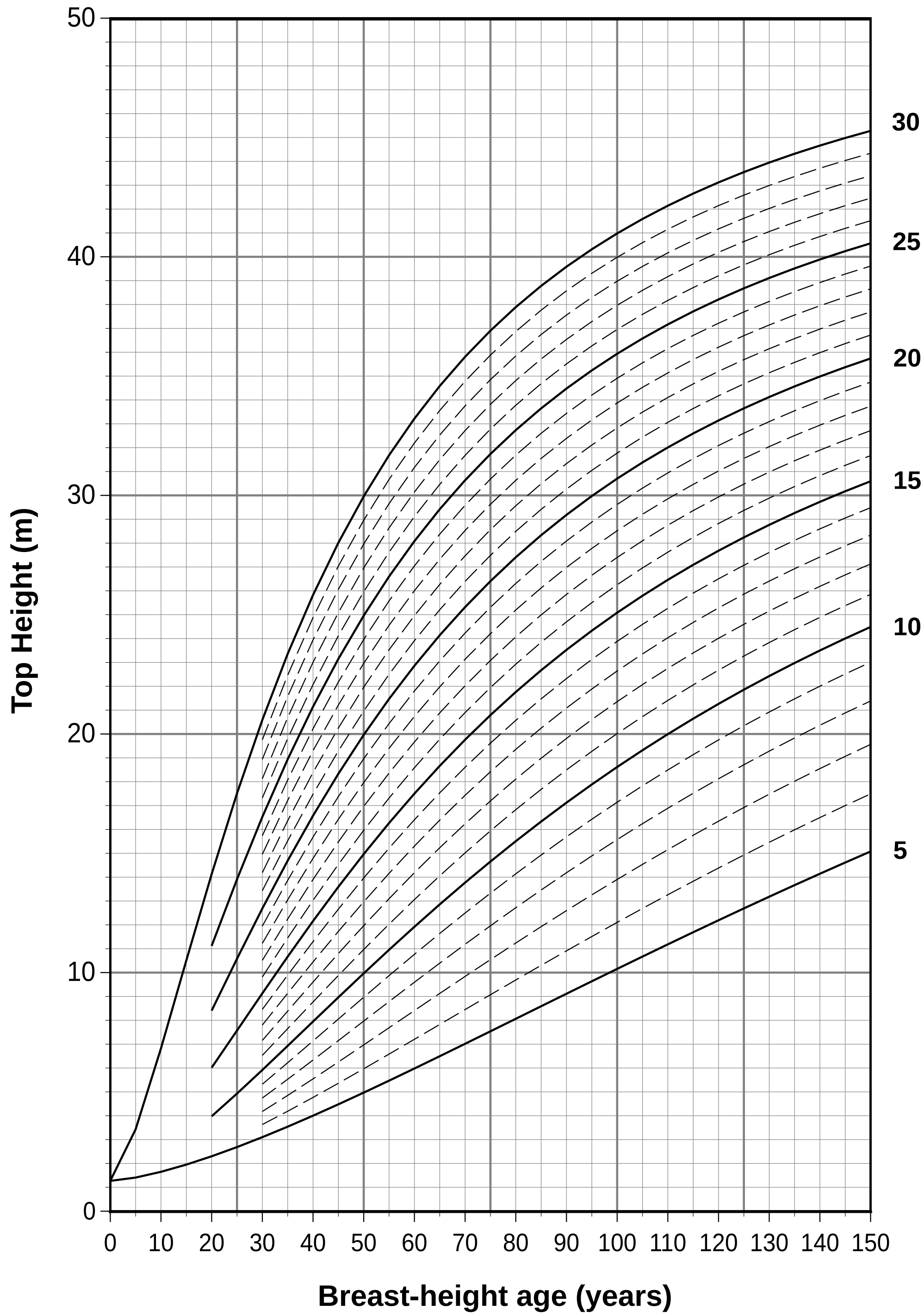
Site index curves for lodgepole pine, white spruce, and interior Douglas-fir

Interior Lodgepole Pine



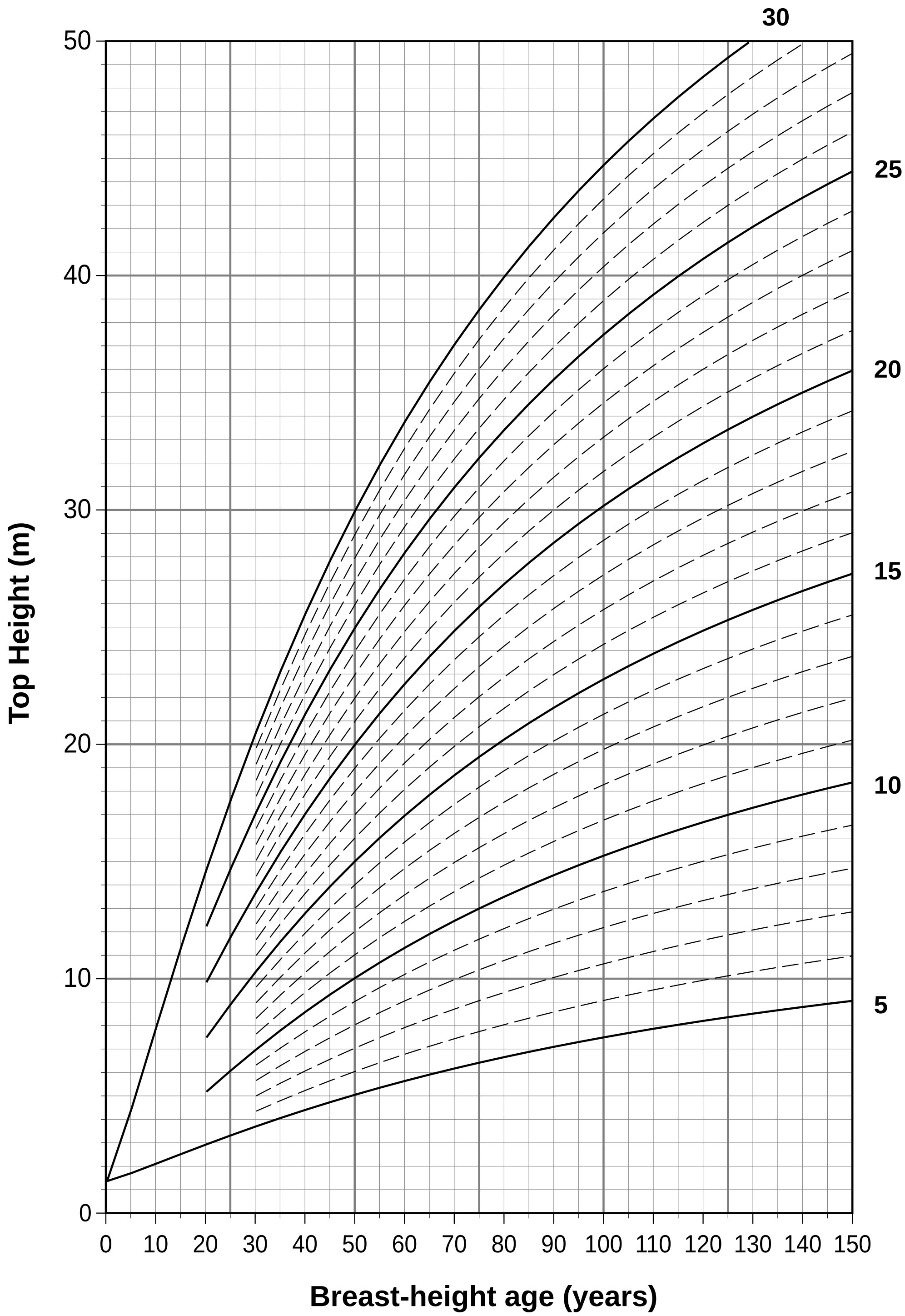
Site Index	5	6	7	8	9-10	11-14	15-22	≥23
Years to bh	14	13	12	11	10	9	8	7

Interior White Spruce



Site Index	5	6	7	8	9	10	11	12-13	14-15	16-17	18-20	21-25	26-33	≥34
Years to bh	26	23	20	18	16	15	14	13	12	11	10	9	8	7

Interior Douglas-fir

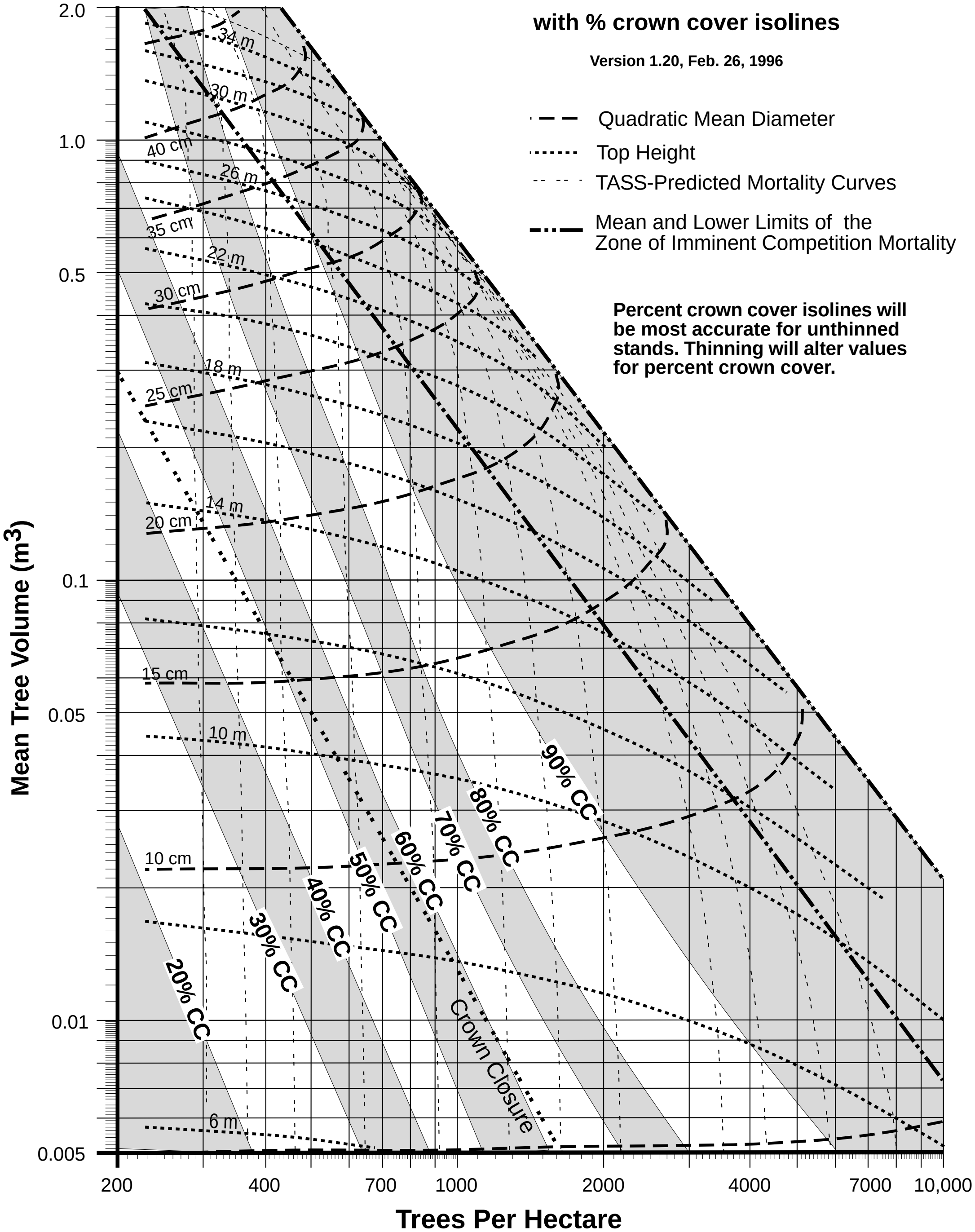


Site Index	5	6	7	8	9	10	11	12-13	14-15	16-18	19-22	23-28	≥29
Years to bh	24	21	18	16	15	14	13	12	11	10	9	8	7

Appendix III

Stand density management diagrams with percent crown cover for lodgepole pine, white spruce, and interior Douglas-fir

Stand Density Management Diagram
Lodgepole Pine (Natural Stands)
with % crown cover isolines



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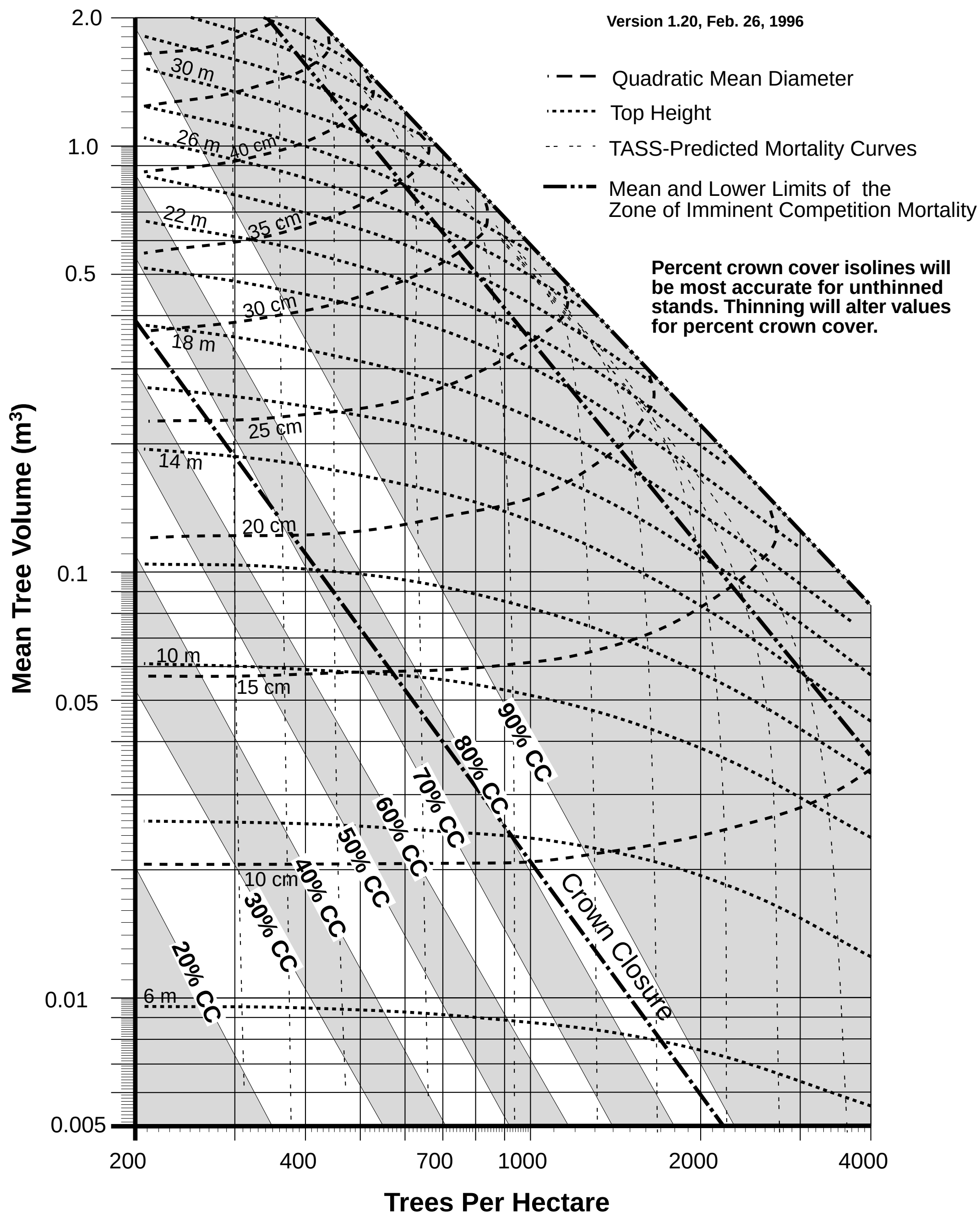
Data Source: TASS-generated managed stand yield tables contained in the computer program WINTIPSY (British Columbia Ministry of Forests, Forest Productivity and Decision Support Section)

Stand Density Management Diagram
Lodgepole Pine (Planted Stands)
with % crown cover isolines



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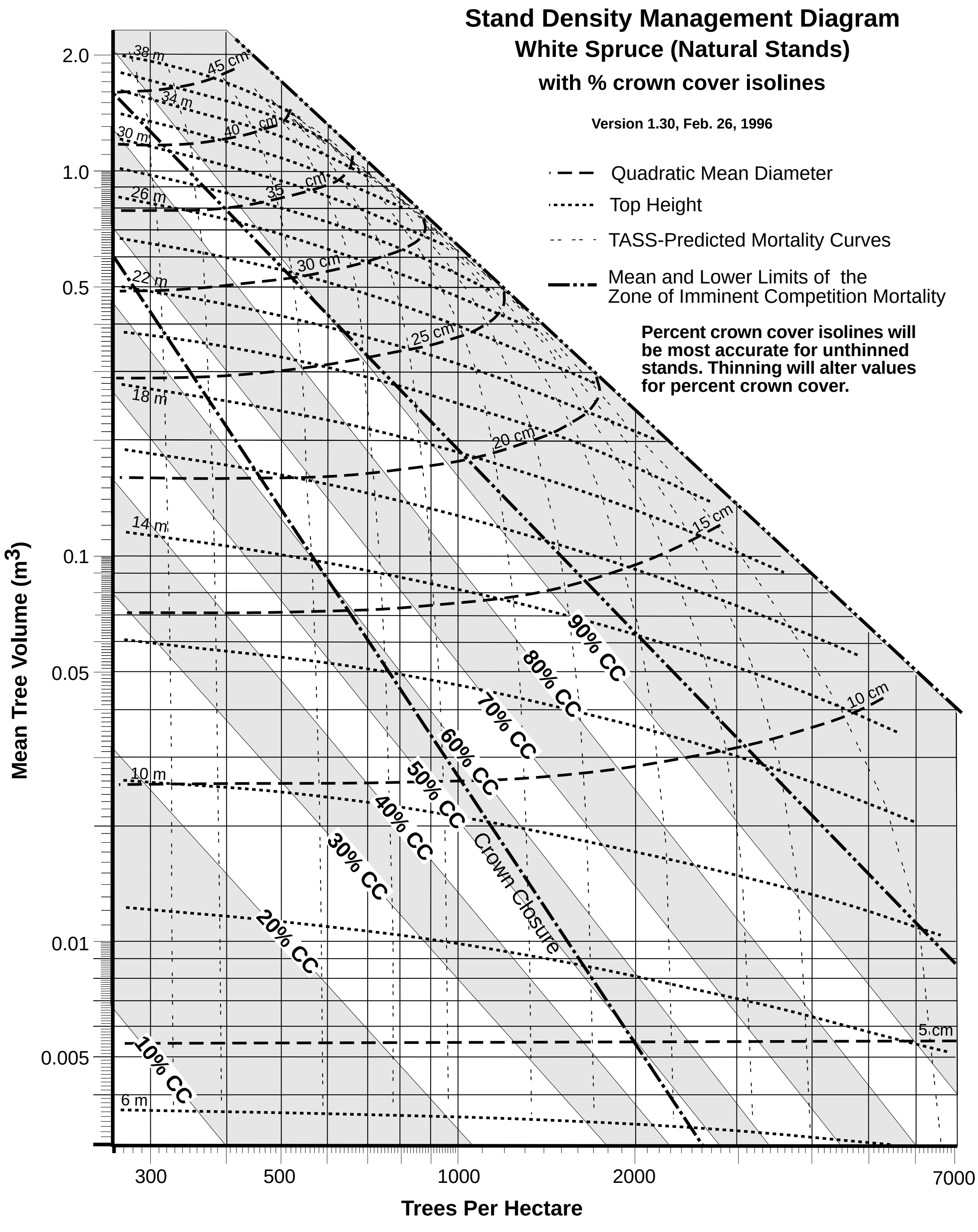

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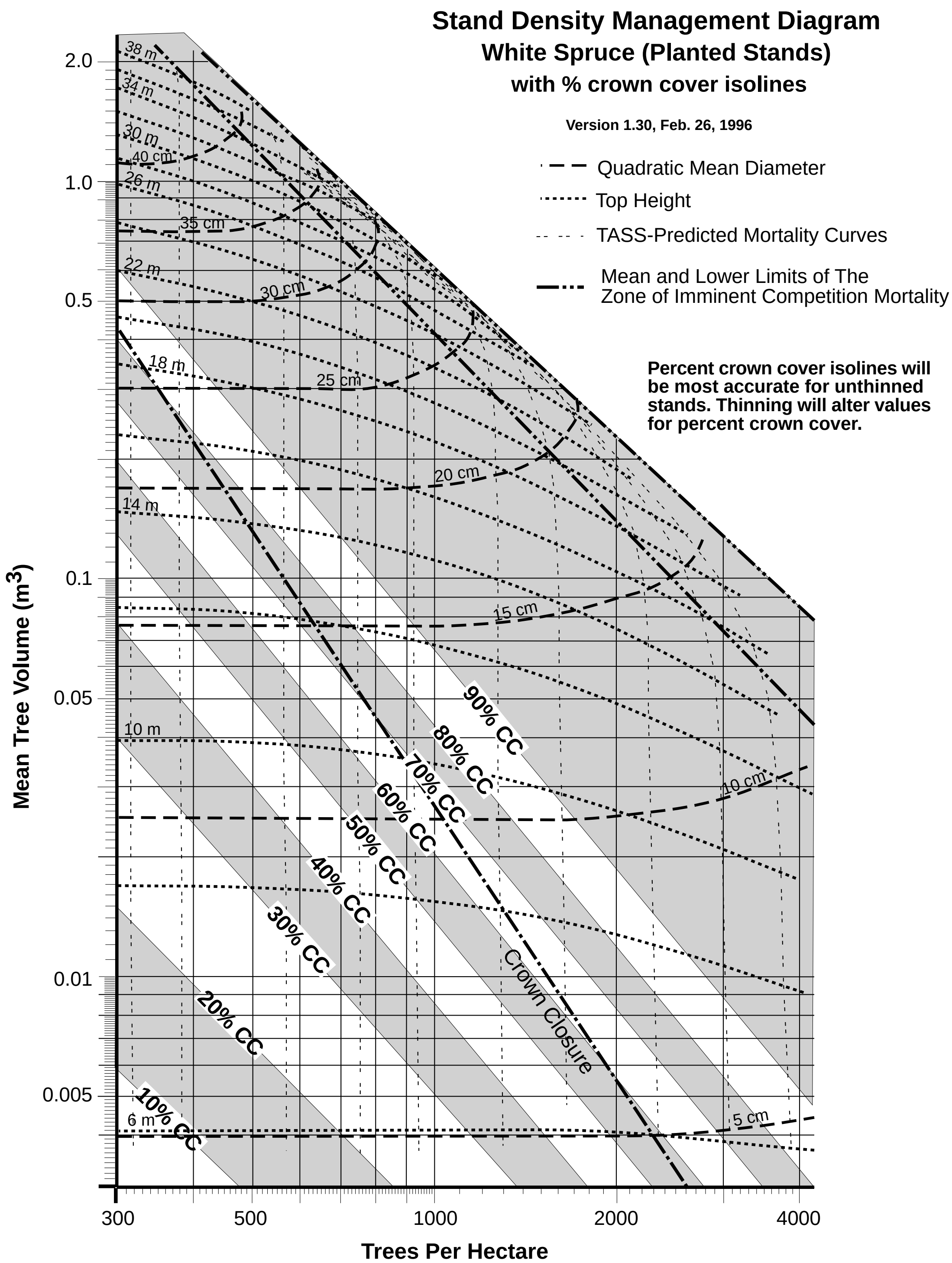

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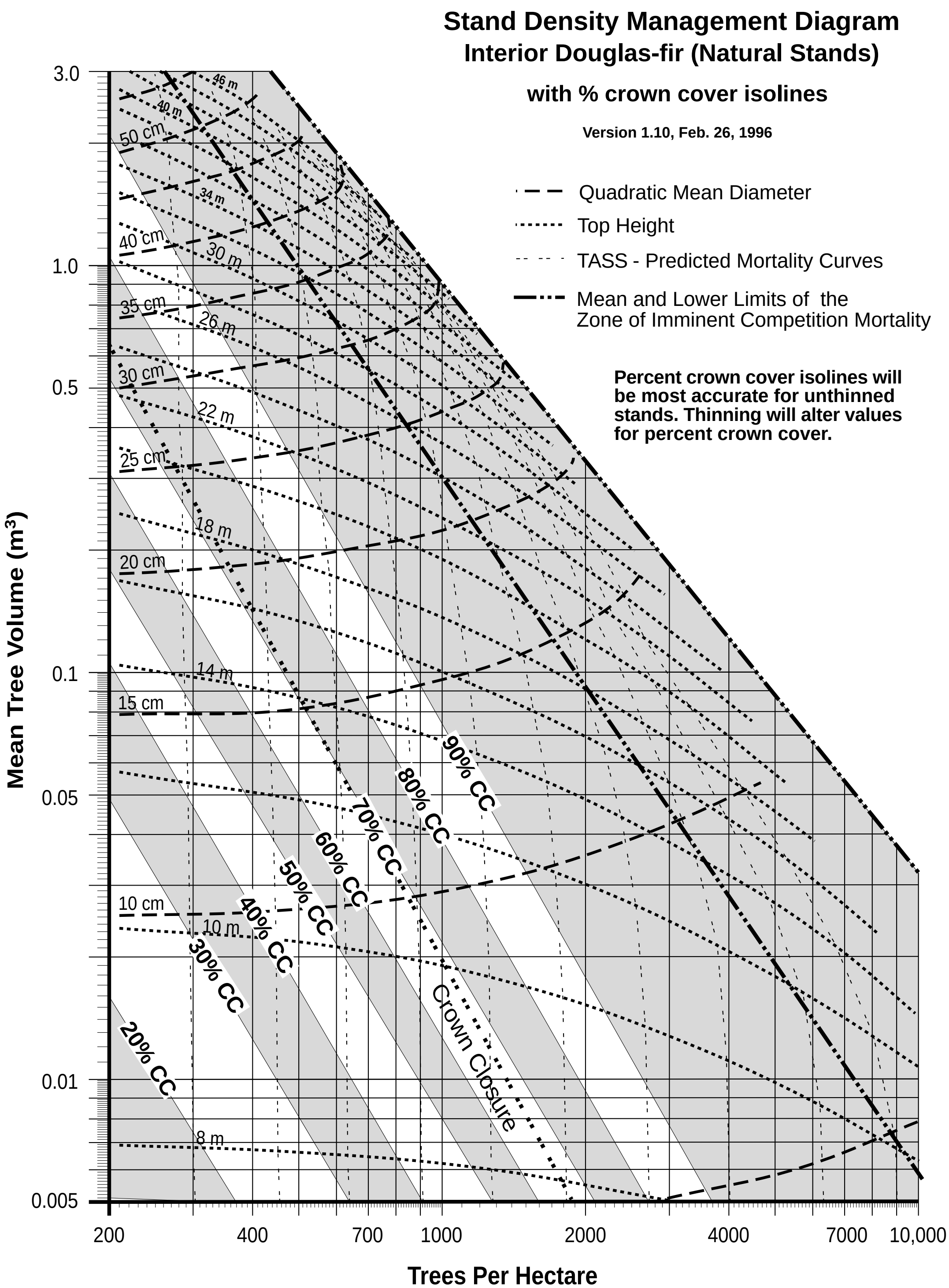

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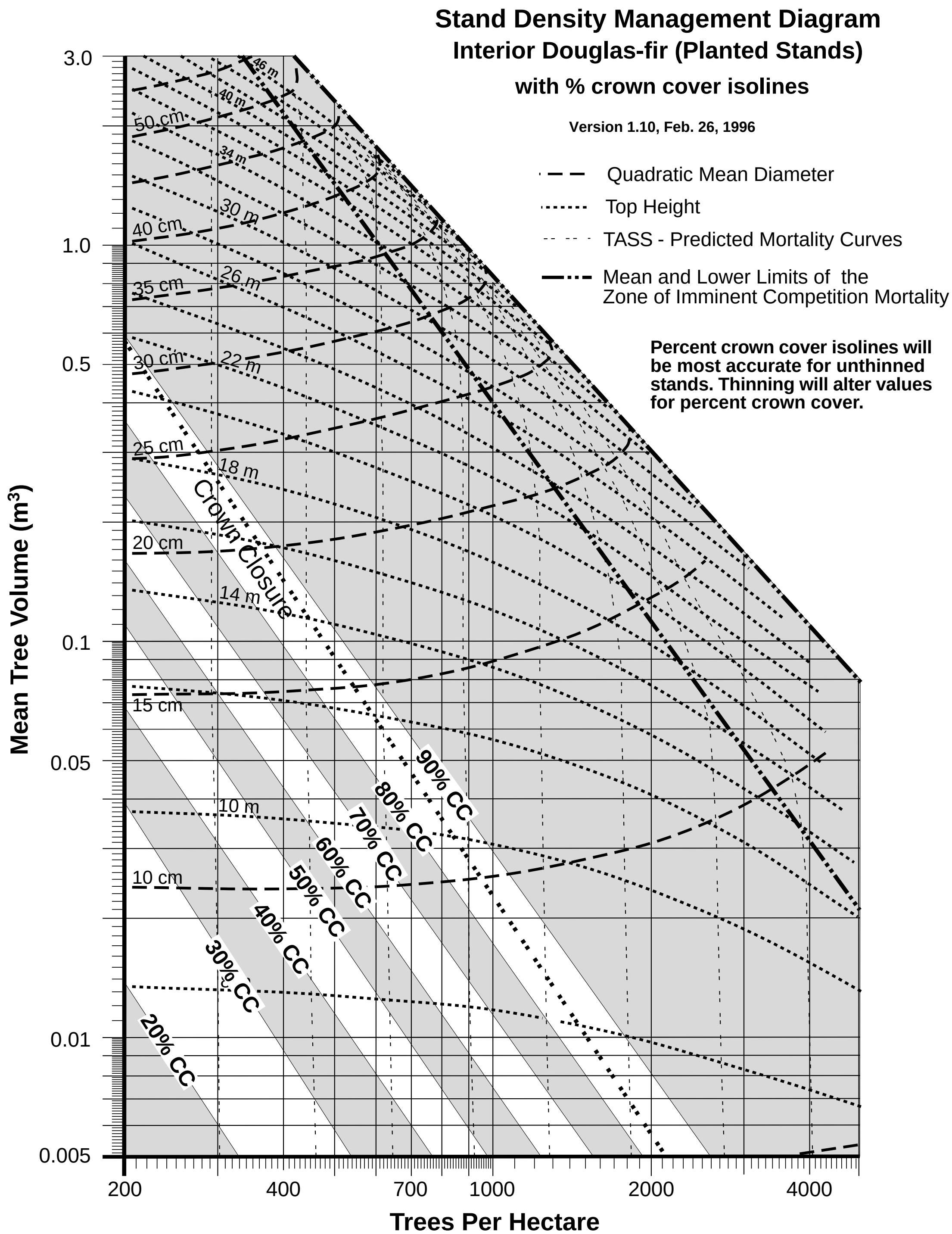

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