Projected Performance of Seedlings Planted under Mountain Pine Beetle Stands

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***Purpose*:** To combine previously synthesized information on growth rates of seedlings under partial canopy and projected light levels under MPB-affected stands over time, to project growth of seedlings planted under MPB stands at different times after attack. Growth is projected for four species (lodgepole pine, Engelmann/hybrid spruce, subalpine fir, Douglas-fir), in modelled stands that vary in several factors affecting growth or light conditions: site index (10, 15, 20, 25m at 50 yr), mean diameter of the MPB-affected stand (10, 25, 40cm), light levels in the stand before MPB (10, 30 and 50% of above-canopy light), non-pine component of the overstory (0, 20 and 40%), and for seedlings planted just after the overstory pines die, or 5, 10, 15 or 20 years later. Height and diameter growth are expressed relative to seedlings planted in a clearcut. Results are also expressed as the number of years that seedlings planted under MPB stands are delayed relative to seedlings in clearcuts. Little empirical information was available on survival of planted seedlings under different canopy levels, so only a simple analysis of survival was undertaken.

Methods

Light projections under MPB and growth-light relationships

Light under MPB stands was projected in a previous report for stands with mean diameters of 10, 25 and 40cm (which affects how fast the snags fall), and with initial lights levels of 10%, 30% and 50% of above-canopy light (representing very dense, moderate and more open stands). Confidence intervals were generated for the projected light curves, based on the undertainties in the input parameters. In a separate report, available literature on the relative diameter and height growth of seedlings with different light levels under partial canopies was synthesized. Relationships between relative growth rates and light were developed for four species that might be planted under MPB (Pl lodgepole pine, Sx Engelmann hybrid spruce, Bl subalpine fir and Fd Douglas-fir). Confidence intervals were also generated, based on the variation among studies of each species. The limited information on survival of seedlings planted under partial canopy was also collated.

Combining light projections and growth-light relationships: Shade-delayed TIPSY growth

To combine the light projections and growth-light relationships, TIPSY height and diameter growth curves were first extracted for each species, under 4 site index values (10, 15, 20 and 25m at 50 years)[1]. The seedlings were then grown under the MPB stand for 90 years, following the TIPSY curve but with an effective age that was reduced in proportion to the reduction in relative growth given the under-canopy light levels in that year. For example, if seedlings were planted at year 1 after MPB when light levels light levels in the MPB-affected stand were 30%, and Pl height growth under 30% light was 40% that of an open-grown seedling, the underplanted seedlings was considered to effectively age 0.4 years from year 1 to year 2 (Figure 1). Therefore, its height at year 2 would be the appropriate TIPSY height curve interpolated at 1.4 years (versus an open growth seedlings that would have the 2-year TIPSY height after 2 years). If the light levels in the second year produced relative height growth of 42% for the underplanted seedling, it would have an effective age of 1.82 years (=1+0.4+0.42) after 3 years, and its height would be the interpolated TIPSY height at 1.82 years (versus the height at 3 years for the open-grown seedling). This year-by-year calculation of effective age continued until

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[1] Curves for Pl were for the MS zone, Sx and Bl in ESSF and Fd in IDF, all in the Penticton district. However, BEC zone and district seems to have little or no effect on TIPSY results (at a given SI value).

the MPB stand was completely decayed, leaving 100% above-canopy light, at which time the underplanted seedlings' effective age would be increasing by 1 year each year.

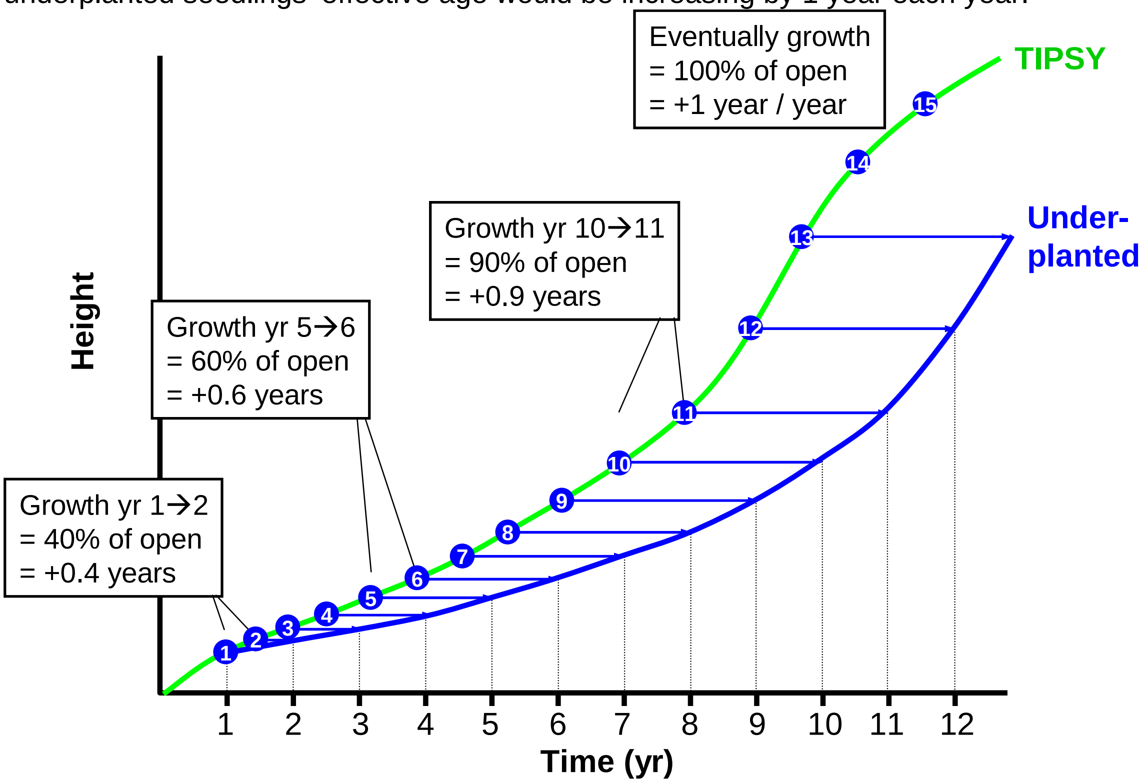

Figure 1. Illustration of delayed-TIPSY approach, for height growth. Growth of underplanted seedlings follow the TIPSY curve for open-grown seedlings, but more slowly when shade reduces growth. See text for further explanation.

Following the TIPSY growth curves, with growth appropriately slowed for the (changing) understory shade levels, means that underplanted and open-grown seedlings follow the same relationship between growth and size, a gentle S-shape function in TIPSY. The underplanted seedlings just follow that relationship more slowly. The difference between the effective age of the underplanted seedlings and their actual age when the MPB-affected overstory has completely decayed shows how much delay in seedling growth the overstory shading causes. In the example in Figure 1, the MPB-killed canopy has disappeared by year 14, at which time the underplanted seedlings are following the TIPSY curve at the same rate as open-grown seedlings (1 year per year), but the underplanted seedlings are ~3.5 years behind. That underplanting scenario would therefore produce a 3.5-year growth delay compared to open-grown seedlings.

This shade-delayed TIPSY approach was used separately for diameter growth and height growth. This produces two different estimates of growth delay for each scenario, one based on diameter growth, the other on height growth. Because height growth showed less sensitivity to shading (previous report), this means that the shape of the seedlings differed somewhat for the underplanted seedlings (relatively taller and thinner, especially in denser and longer-persisting large-diameter stands).

Delayed planting

Scenarios were run with seedlings underplanted just after the MPB-affected pine died, and 5, 10, 15 and 20 years later[2]. The scenarios with planting delays were analysed in the same

[2] The synthesis of studies of fall rates of pine snags did not show strong evidence of an initial lag time with low fall rates. If such a lag period is expected in certain stand types – including the time for beetles to enter

way as the no-delay scenarios, except that light levels for adjusting the progress along the TIPSY curve were taken to start 5, 10, 15 or 20 years after the MPB attack.

Non-pine overstory in the MPB stand

The scenarios with 25cm dbh average overstory and 30% light under the live stand, including planting delays from 0-20 years, were also run with 20% and 40% non-pine overstory. The non-pine overstory component was assumed to remain alive and the same size after MPB attack (which could reflect a balance between additional mortality and growth of these residual trees). The residual non-pine trees were assumed to be well-distributed through the stand. Their (constant) shade was added to the (changing) shade from the decaying dead pine.

Partial overstory removal

Additional scenarios were run with 30%, 50% and 70% removal of the dead pine overstory, which was assumed to occur when the trees first died. These scenarios were run for the different planting delays in stands with SI 15, 25cm dbh overstory with 30% initial light, for both pure pine stands and stands with 20% non-pine overstory. The partial removals only affected the dead pines, not the live non-pine component.

Survival

Three simple curves, representing the "low", "medium" and "high" extremes of the limited available data, were fit by hand (Figure 2.) The curves used the combined data for the 4 species, as there was too little information to separate species. However, the curves corresponded exactly or closely to Coates and Hall's (2005) survival values for lodgepole pine at low light.

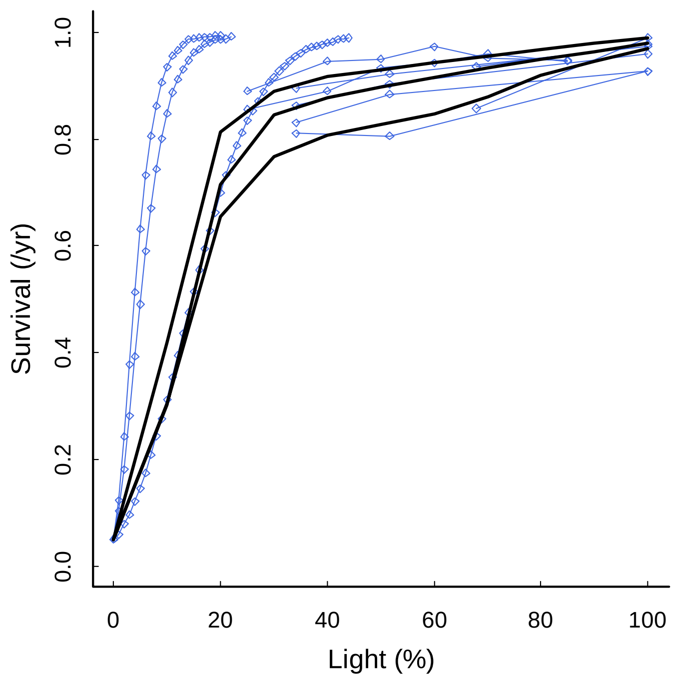

Figure 2. All available data on survival of planted seedlings versus light (percent of above-canopy levels) (blue) and 3 hand-fitted curves representing "low", "medium" and "high" parts of the available data. The three curves are all close to the survival values for lodgepole pine at lower light (ignoring the much higher survival of subalpine fir and spruce). Note that survival rates are <1 at 100% light.

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the stand and actually kill the pine trees – then the results presented here could be treated as if time 0 was at the end of the no-snag-fall lag time.

Each curve was used project 5-, 10- and 20-year survival of seedlings planted under the different scenarios (different planting delays, average dbh and initial light levels). Survival remained <1 at 100% light, because seedlings planted in clearcuts also experience annual mortality. The annual survival rates of 0.99 ("high" curve), 0.98 ("medium") and 0.97 ("low") at 100% light correspond to 20 year survival rates of seedlings planted in clearcuts of 81.8%, 66.8% and 54.4% respectively. I assumed that the 2 lower datapoints at 100% light represented anomalously high initial mortality of seedlings planted in clearcut treatments, which would not be maintained for the longer-term.

Results

Growth under pure pine stands killed by MPB

Growth curves for diameter[3] and height for all 12 combinations of site index and initial light conditions are shown in Appendix 1. Each graph shows the TIPSY growth curve for open-grown seedlings, and the growth curve for seedlings planted under a pure pine MPB-killed stand, with 0, 5, 10, 15 and 20 years delay before planting. The results for site index 15 or 20, initial light 30% are probably the most representative of "average conditions" for southern Interior stands. Dotted lines are 95% confidence intervals based on uncertainties in the input parameters.

Table 1 shows the delay in growth for underplanted seedlings compared to seedlings planted in the open, with a longer effective delay for growth based on diameter, which is more sensitive to shading than height growth. The results are for SI=15, but SI has negligible effect on the effective delay (see "Site Index" below).

Overall, the initial shading from the dead pines has a clear effect on delaying growth of the underplanted seedlings. Factors affecting the degree of growth delay include:

<u>Planting delay</u>: The growth delay is necessarily at least as long as the planting delay. With a 20-year planting delay, the growth delay is only slightly more than 20 years, indicating that the mostly open overstory this long after MPB mortality has little effect on seedling growth. On the other hand, with no planting delay, underplanted seedlings end up 4.8-13.3 years (for diameter) or 2.6-8.6 years (for height) behind open-planted seedlings, due to shade effects particularly in the initial years. Depending on species, initial light levels and overstory dbh, delaying planting 10 years results in an additional growth delay of 2-8 years compared to planting immediately after pine mortality. The better growth under the more open later stand partially compensates for the planting delay. Similarly, planting 5 years after death of the overstory pine produces only slightly more delay in growth in the longer-term than planting immediately after MPB mortality. After 10 years, additional delay in planting is more directly added to the net growth delay. So, for example, changing from planting 10 years after pine death to 15 years delays the seedlings by almost 5 additional years, and changing from 15 to 20 years adds another 5 years. There is little growth compensation at this point, because the decaying dead stand has already become mostly open.

<u>Measure (diameter versus height)</u>: Height growth is less delayed by initial shade than diameter growth, because relative height growth is less affected by moderate shade (previous report). The change from 0 years planting delay to 10 years therefore has little net effect on diameter growth (because diameter growth is very slow in the initial dark stand, so faster growth in the lighter stand after 10 years mostly compensates for the delay), while height growth, which is less affected by initial shade, shows a greater effect of the 10-year delay.

<u>Initial stand openness</u>: As expected, darker (denser) initial stands have slower growth. There is also less net difference between 0 year and 10 year planting delays in the darkest stands,

[3] Diameter is measured at 2m (following TIPSY convention), and so remains at 0cm until the trees are 2m tall.

because trees planted in the dark initial conditions grow very little until the stand starts to become more open.

Species: The delay in growth is most pronounced for lodgepole pine and least for subalpine fir, reflecting the relative shade tolerance of the species. The more shade-intolerant species show the least net growth difference between 0-year and 10-year planting delays.

Site index: SI obviously affects the absolute rate of growth in the open and for the underplanted seedlings, but it had negligible effect on the *relative* differences between open and underplanted trees and between the different planting delays. Essentially, the results just scaled up proportionally as SI increased, so that SI does not affect the relative growth difference or the effective delay time for the underplanting scenarios.

Average overstory diameter: Results in Appendix 1 are only shown for stands with average dbh of 25cm. Growth of underplanted seedlings was slightly faster under 10cm MPB-killed trees, because these snags fell more quickly, producing more light earlier. Results for 40cm overstory differed little from the 25cm results, because foliage and branch loss, assumed to be independent of snag size, was the dominant process in opening up the dead canopy with these longer-standing larger snags. Table 1 does illustrate the moderate differences in delay times in underplanted seedling growth between 10cm and 25+cm overstory dbh.

Table 1. Predicted delay (years) in seedling growth (based on diameter in top table, height in bottom table) due to shading under MPB-killed stands, as a function of species, planting delay after pine death, average overstory diameter and light conditions in the initial live stand (percent above-canopy light).

Diameter growth

		10cm DBH			25cm DBH			40cm DBH		
Species	**Delay**	**10%[1]**	**30%**	**50%**	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
Lodgepole pine										
	0 years	9.6	6.7	4.8	12.1	8.6	6.1	13.3	9.5	6.8
	5 years	10.4	8.6	7.5	12.7	10.2	8.6	13.9	11.1	9.2
	10 years	12.6	11.7	11.3	14.3	12.8	12.0	15.3	13.4	12.3
	15 years	16.2	16.0	15.8	17.1	16.4	16.1	17.8	16.8	16.3
	20 years	20.9	20.8	20.7	21.4	21.0	20.9	21.9	21.3	21.0
Engelmann spruce										
	0 years	7.2	4.7	3.1	9.2	6.0	4.0	10.2	6.7	4.5
	5 years	8.7	7.3	6.5	10.4	8.4	7.3	11.3	9.0	7.6
	10 years	11.6	11.1	10.8	12.8	11.7	11.2	13.5	12.1	11.4
	15 years	15.7	15.6	15.5	16.3	15.9	15.7	16.7	16.1	15.8
	20 years	20.5	20.5	20.4	20.8	20.6	20.5	21.1	20.8	20.6
Subalpine fir										
	0 years	6.3	3.9	2.6	8.2	5.1	3.3	9.1	5.7	3.7
	5 years	8.1	6.9	6.2	9.7	7.8	6.8	10.5	8.3	7.1
	10 years	11.3	10.9	10.6	12.3	11.4	10.9	12.9	11.7	11.1
	15 years	15.6	15.5	15.4	16.0	15.7	15.5	16.4	15.9	15.6
	20 years	20.4	20.4	20.3	20.7	20.5	20.4	20.9	20.6	20.5
Douglas-fir										
	0 years	7.4	5.0	3.4	9.4	6.4	4.4	10.4	7.1	4.8
	5 years	9.0	7.5	6.7	10.8	8.7	7.4	11.7	9.4	7.8
	10 years	11.8	11.2	10.9	13.0	11.9	11.3	13.8	12.3	11.6
	15 years	15.9	15.7	15.6	16.4	16.0	15.8	16.9	16.2	15.9
	20 years	20.6	20.6	20.5	21.0	20.7	20.6	21.3	20.9	20.7

[1] Light levels in live stand

Table 1 Cont'd
Height growth

Species	Delay	10cm DBH 10%[1]	30%	50%	25cm DBH 10%	30%	50%	40cm DBH 10%	30%	50%
Lodgepole pine										
	0 years	5.9	3.6	2.6	7.6	4.6	3.2	8.6	5.1	3.6
	5 years	7.9	7.0	6.4	9.3	7.8	7.0	10.1	8.2	7.3
	10 years	11.4	11.0	10.7	12.3	11.5	11.1	12.8	11.9	11.3
	15 years	15.7	15.5	15.5	16.2	15.8	15.6	16.6	16.0	15.8
	20 years	20.5	20.4	20.4	20.8	20.6	20.5	21.1	20.7	20.6
Engelmann spruce										
	0 years	4.5	2.2	1.1	6.0	3.1	1.5	6.7	3.5	1.7
	5 years	6.7	5.7	5.4	7.9	6.3	5.6	8.4	6.6	5.7
	10 years	10.4	10.2	10.2	11.0	10.4	10.3	11.4	10.6	10.3
	15 years	15.2	15.1	15.1	15.3	15.2	15.1	15.4	15.2	15.2
	20 years	20.1	20.1	20.1	20.2	20.1	20.1	20.2	20.2	20.1
Subalpine fir										
	0 years	4.3	2.2	1.1	5.8	3.0	1.5	6.5	3.4	1.7
	5 years	6.6	5.7	5.3	7.7	6.3	5.5	8.2	6.6	5.7
	10 years	10.4	10.2	10.1	10.9	10.4	10.2	11.2	10.5	10.2
	15 years	15.1	15.1	15.1	15.2	15.1	15.1	15.3	15.1	15.1
	20 years	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1	20.1
Douglas-fir										
	0 years	4.6	3.0	2.2	5.9	3.7	2.8	6.7	4.1	3.0
	5 years	7.4	6.7	6.2	8.4	7.4	6.7	9.0	7.7	6.9
	10 years	11.2	10.8	10.6	11.9	11.3	10.9	12.4	11.6	11.1
	15 years	15.6	15.5	15.4	16.0	15.7	15.5	16.3	15.9	15.6
	20 years	20.4	20.4	20.3	20.6	20.5	20.4	20.9	20.6	20.5

[1] Light levels in live stand

Growth delay with some non-pine overstory

Because non-pine overstory does not disappear over time, the scenarios with a non-pine component never have open conditions. Therefore, growth of the underplanted seedlings is always slower than the TIPSY curve. The growth delay is therefore presented for a TIPSY age of 40 years – i.e., the extra time it takes the underplanted seedlings to reach the diameter or height of a 40 year-old open-grown seedling.

For lodgepole pine diameter growth, which is most sensitive to shading, growth to 40-year diameter under MPB-affected stands is delayed an additional ~20 years with 20% non-pine, and an additional ~40 years with 40% non-pine (Table 2). The additional delay for diameter growth of the more shade-tolerant species is about 6-10 years for 20% non-pine and 15-22 years for 40% non-pine. Height growth is less affected by the persistent shading from the 20% or 40% non-pine overstory components, with ~7 years additional delay for lodgepole pine under 20% non-pine stands after MPB, and ~ 12 additional years under 40% non-pine. For the other species, additional delays in height growth compared to pure pine stands are 2-5 years with 20% non-pine and 7-10 years with 40% non-pine.

Table 2. Delay in reaching the diameter (left) or height (right) of a 40-year-old open-grown seedling for seedlings of 4 species planted under MPB-affected stands with 0% non-pine (i.e. pure pine), 20% non-pine or 40% non-pine in the overstory.

Diameter growth

		Non-pine overstory		
Species	**Delay**	**0%**	**20%**	**40%**
Lodgepole pine				
	0 years	8.6	23.1	43.5
	5 years	10.2	25.3	46.4
	10 years	12.8	28.3	50.1
	15 years	16.4	32.1	54.3
	20 years	21.0	36.8	59.1
Engelmann spruce				
	0 years	6.0	14.0	24.3
	5 years	8.4	16.9	27.7
	10 years	11.7	20.4	31.6
	15 years	15.9	24.6	36.1
	20 years	20.6	29.4	40.9
Subalpine fir				
	0 years	5.1	11.3	19.3
	5 years	7.8	14.3	22.8
	10 years	11.4	18.1	26.8
	15 years	15.7	22.4	31.3
	20 years	20.5	27.2	36.1
Douglas-fir				
	0 years	6.4	15.0	27.1
	5 years	8.7	17.8	30.5
	10 years	11.9	21.3	34.4
	15 years	16.0	25.4	38.8
	20 years	20.7	30.2	43.7

Height growth

		Non-pine overstory		
Species	**Delay**	**0%**	**20%**	**40%**
Lodgepole pine				
	0 years	4.6	10.4	15.2
	5 years	7.8	13.9	19.0
	10 years	11.5	18.2	23.5
	15 years	15.8	22.7	28.3
	20 years	20.6	27.6	33.2
Engelmann spruce				
	0 years	3.1	5.6	10.9
	5 years	6.3	8.9	14.5
	10 years	10.4	12.9	18.6
	15 years	15.2	17.4	23.1
	20 years	20.1	22.3	27.9
Subalpine fir				
	0 years	3.0	5.7	11.6
	5 years	6.3	9.0	15.3
	10 years	10.4	12.9	19.5
	15 years	15.1	17.4	24.1
	20 years	20.1	22.3	28.9
Douglas-fir				
	0 years	3.7	8.6	12.3
	5 years	7.4	12.8	16.8
	10 years	11.3	17.2	21.6
	15 years	15.7	21.9	26.5
	20 years	20.5	26.7	31.5

Growth delay with partial overstory removal

Overstory removal reduces the growth delay, most strongly for seedlings planted immediately after harvest (Table 3). In pure pine stands, the predicted reduction in growth delay is almost proportional to the percent removal in scenarios with no planting delay (i.e., a 50% removal reduces the growth delay almost 50%, with some variation among species; Table 3a). The effect of overstory removal diminishes as the planting delay increases, because the seedlings are exposed to decreasing amounts of shade with longer planting delays (so that the planting delay itself is the dominant component of the growth delay, not shading effects). With a 20% non-pine component, the effect of partial removal of the dead pines is relatively small, because most of the shading comes from the persistent live non-pine component (Table 3b).

Table 3. Predicted delay (years) in seedling growth (based on diameter in right table, height in left table) planted under MPB-affected stands with different degrees of overstory removal, in a.) a pure pine stand, and b. a stand with 80% pine, 20% non-pine. Results are for SI 15, 25cm dbh overstory with 30% initial light.

a. 100% pine

Diameter growth

		Canopy removal			
Species	**Delay**	0%	30%	50%	70%
Lodgepole pine					
	0 years	8.6	6.8	5.4	3.7
	5 years	10.2	9.0	8.1	7.2
	10 years	12.8	12.1	11.7	11.2
	15 years	16.4	16.1	15.9	15.8
	20 years	21.0	20.8	20.7	20.6
Engelmann spruce					
	0 years	6.0	4.6	3.5	2.3
	5 years	8.4	7.6	6.9	6.3
	10 years	11.7	11.3	11.0	10.7
	15 years	15.9	15.6	15.6	15.5
	20 years	20.6	20.5	20.4	20.4
Subalpine fir					
	0 years	5.1	3.8	2.9	1.9
	5 years	7.8	7.1	6.6	6.0
	10 years	11.4	11.0	10.8	10.6
	15 years	15.7	15.5	15.4	15.4
	20 years	20.5	20.4	20.3	20.3
Douglas-fir					
	0 years	6.4	4.9	3.8	2.5
	5 years	8.7	7.7	7.1	6.4
	10 years	11.9	11.4	11.1	10.8
	15 years	16.0	15.7	15.6	15.5
	20 years	20.7	20.6	20.5	20.5

Height growth

		Canopy removal			
Species	**Delay**	0%	30%	50%	70%
Lodgepole pine					
	0 years	4.6	3.5	2.9	2.0
	5 years	7.8	7.2	6.7	6.2
	10 years	11.5	11.2	10.9	10.7
	15 years	15.8	15.6	15.5	15.4
	20 years	20.6	20.4	20.4	20.4
Engelmann spruce					
	0 years	3.1	2.0	1.2	0.6
	5 years	6.3	5.8	5.5	5.3
	10 years	10.4	10.3	10.2	10.2
	15 years	15.2	15.1	15.1	15.1
	20 years	20.1	20.1	20.1	20.1
Subalpine fir					
	0 years	3.0	1.9	1.2	0.5
	5 years	6.3	5.7	5.4	5.2
	10 years	10.4	10.2	10.1	10.1
	15 years	15.1	15.1	15.1	15.1
	20 years	20.1	20.1	20.1	20.0
Douglas-fir					
	0 years	3.7	3.0	2.5	1.7
	5 years	7.4	6.8	6.4	6.0
	10 years	11.3	11.0	10.8	10.6
	15 years	15.7	15.5	15.4	15.4
	20 years	20.5	20.4	20.3	20.3

Table 3 Cont'd.
b. 80% pine, 20% non-pine

Diameter growth

Species	Delay	Canopy removal 0%	30%	50%	70%
Lodgepole pine					
	0 years	23.1	21.5	20.5	19.1
	5 years	25.3	24.3	23.6	22.8
	10 years	28.3	27.7	27.4	27.0
	15 years	32.1	31.9	31.8	31.6
	20 years	36.8	36.6	36.6	36.5
Engelmann spruce					
	0 years	14.0	12.8	11.9	10.9
	5 years	16.9	16.1	15.6	15.1
	10 years	20.4	20.0	19.8	19.6
	15 years	24.6	24.5	24.4	24.3
	20 years	29.4	29.3	29.3	29.2
Subalpine fir					
	0 years	11.3	10.1	9.3	8.5
	5 years	14.3	13.6	13.2	12.7
	10 years	18.1	17.7	17.5	17.3
	15 years	22.4	22.3	22.2	22.1
	20 years	27.2	27.1	27.1	27.1
Douglas-fir					
	0 years	15.0	13.7	12.8	11.8
	5 years	17.8	16.9	16.4	15.8
	10 years	21.3	20.7	20.5	20.3
	15 years	25.4	25.2	25.1	25.0
	20 years	30.2	30.0	30.0	29.9

Height growth

Species	Delay	Canopy removal 0%	30%	50%	70%
Lodgepole pine					
	0 years	10.4	9.4	8.9	8.4
	5 years	13.9	13.5	13.2	12.9
	10 years	18.2	17.9	17.7	17.6
	15 years	22.7	22.5	22.5	22.4
	20 years	27.6	27.4	27.4	27.4
Engelmann spruce					
	0 years	5.6	4.6	3.9	3.1
	5 years	8.9	8.3	8.0	7.6
	10 years	12.9	12.6	12.5	12.4
	15 years	17.4	17.3	17.3	17.3
	20 years	22.3	22.3	22.3	22.2
Subalpine fir					
	0 years	5.7	4.8	4.1	3.3
	5 years	9.0	8.5	8.1	7.7
	10 years	12.9	12.7	12.6	12.4
	15 years	17.4	17.4	17.4	17.3
	20 years	22.3	22.3	22.3	22.3
Douglas-fir					
	0 years	8.6	7.9	7.6	7.2
	5 years	12.8	12.2	12.1	11.8
	10 years	17.2	16.8	16.6	16.5
	15 years	21.9	21.5	21.4	21.4
	20 years	26.7	26.4	26.3	26.3

Survival

Projected 5-, 10- and 20-year survival of seedlings under the various combinations of survival curves, planting delay, overstory size and live-stand light levels are in Appendix 1.

The 3 curves of possible relationships between survival and light levels have substantial effects on the absolute 5-, 10- and 20-year survival rates (projected actual 10-year survival in Table 4a). However, the pattern of relative survival with respect to planting delay, initial light levels and overstory size – including projections for clearcuts – remains similar with the different rates. In other words, the projected survival in different understory conditions relative to survival in clearcuts differs relatively little among the projections using "low", "medium" and "high" rates (survival relative to the clearcut shown in Table 4b). The main difference is that the low curve emphasizes the poor survival of seedlings planted immediately after MPB or 5 years later in dense stands.

Table 4. Projected 10-year survival of seedlings planted under MPB-killed stands, as a function of planting delay, overstory diameter and initial light levels in the live stand (percent above-canopy light). Projections are for <u>medium</u> survival curves. Values in a. are actual projected survival, values in b. are relative to projected survival in clearcuts (using the same survival curve).

a. ABSOLUTE 10-YEAR SURVIVAL

	LOW Survival (C/C=0.737)			MEDIUM Survival (C/C=0.817)			HIGH Survival (C/C=0.904)		
	DBH 25cm			DBH 25cm			DBH 25cm		
Delay	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.016	0.173	0.278	0.032	0.361	0.496	0.092	0.504	0.627
5 years	0.171	0.302	0.445	0.355	0.515	0.622	0.497	0.646	0.739
10 years	0.375	0.522	0.612	0.571	0.674	0.730	0.699	0.787	0.837
15 years	0.614	0.671	0.702	0.730	0.771	0.792	0.839	0.870	0.885
20 years	0.671	0.705	0.720	0.771	0.795	0.806	0.870	0.887	0.894

b. 10-YEAR SURVIVAL RELATIVE TO CLEARCUT (=100%)

	LOW Survival			MEDIUM Survival			HIGH Survival		
	DBH 25cm			DBH 25cm			DBH 25cm		
Delay	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	2.2	23.4	37.8	3.9	44.1	60.7	10.1	55.8	69.4
5 years	23.2	41.0	60.4	43.5	63.1	76.1	55.0	71.4	81.8
10 years	50.9	70.8	83.0	69.9	82.5	89.3	77.3	87.1	92.5
15 years	83.3	91.1	95.2	89.3	94.3	97.0	92.8	96.3	97.9
20 years	91.1	95.7	97.7	94.3	97.3	98.6	96.3	98.1	98.9

With the medium survival curve, severely poor survival only occurs for seedlings planted immediately after MPB mortality in dense stands (Table 5). These are the only conditions that subject the seedlings to the low light levels where Coates and Hall (2005) predict high annual mortality. (These light levels are below the levels recorded in the other studies with survival information.) Larger diameter pine stands exacerbate the effect, because these snags remain standing for longer.

Moderately low 5-year survival (<70%) was also predicted with a 5-year delay in the densest stands, and with no delay in the moderate-density stands. By 20 years post-planting, <40% of these seedlings are expected to be surviving. Projected 20-year survival in clearcuts was 0.668. Seedlings planted 15 or 20 years after MPB mortality had projected survival rates close to this level, because they are only exposed to light shading for a few years.

These survival projections are subject to many caveats (see discussion).

Table 5. Projected 5-, 10- and 20-year survival of seedlings planted under MPB-killed stands, as a function of planting delay, overstory diameter and initial light levels in the live stand (percent above-canopy light). Projections are for medium survival curves.

5-year survival **CLEARCUT = 0.904**

	DBH 10cm			DBH 25cm		
Delay	**10%**[1]	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.153	0.603	0.707	0.074	0.580	0.688
5 years	0.643	0.752	0.815	0.561	0.695	0.778
10 years	0.790	0.845	0.872	0.709	0.798	0.841
15 years	0.887	0.900	0.907	0.854	0.881	0.897
20 years	0.904	0.910	0.912	0.884	0.900	0.906

10-year survival **CLEARCUT = 0.817**

	DBH 10cm			DBH 25cm		
Delay	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.084	0.412	0.540	0.032	0.361	0.496
5 years	0.468	0.601	0.682	0.355	0.515	0.622
10 years	0.673	0.737	0.769	0.571	0.674	0.730
15 years	0.781	0.800	0.808	0.730	0.771	0.792
20 years	0.806	0.814	0.818	0.771	0.795	0.806

20-year survival **CLEARCUT = 0.668**

	DBH 10cm			DBH 25cm		
Delay	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.052	0.287	0.399	0.016	0.226	0.344
5 years	0.350	0.466	0.536	0.245	0.381	0.476
10 years	0.528	0.585	0.614	0.426	0.521	0.573
15 years	0.624	0.641	0.650	0.563	0.605	0.630
20 years	0.648	0.654	0.657	0.610	0.634	0.645

[1] Light levels in live stand

Discussion

The synthesis presented here predicts that seedlings underplanted in typical pure mature pine stands (25cm average dbh, 30% initial light) that have been killed by MPB will be delayed 5 years (lodgepole pine) or 3 years (other species) in height growth and 9 years (lodgepole pine) or 6 years (other species) in diameter growth. This includes the initial effects of shading in the recently-killed stand and the diminishing effects as the dead pine decay and fall. This delay in growth is not likely to be a large operational issue for long-term timber supply.

A more important factor is the mortality of the underplanted seedlings. Existing empirical information on survival of planted seedlings versus light level under partial cover is very limited. Best guesses at this point suggest substantial mortality with immediate planting in dense stands, and moderate mortality in typical or more open stands. A 5-year planting delay would reduce this mortality, but at least a 10 or 15 year delay is needed for mortality rates similar to those of open-planted seedlings. Again, though, these projections are based on results from only 3 studies, and factors such as size and quality of the planting stock and quality of site preparation and planting undoubtedly have large effects on the survival of underplanted trees. Collecting basic information on seedling survival and light levels is simple (and quicker than growth measurements), and should be incorporated into any operational underplanting of MPB stands.

Delaying planting until 5 or 10 years after pine mortality further delays growth, but not as long as the planting delay – for example, a 10-year delay may only delay growth 3 additional years, because the underplanted seedlings are not subject to the darkest conditions immediately after pine mortality. This partial compensation for delayed planting diminishes after 10 years, so that additional planting delay after 10 years adds almost directly to the total growth delay. The partial compensation for delayed planting is also reduced for stands that are initially more open, and for more shade-tolerant seedlings, such as subalpine fir. Operationally, this may support quicker underplanting in more open MPB-affected stands, and where species other than pine are being replanted. For dense stands and where pine is the favoured species for planting, delaying planting until the decaying stand is moderately open would have little additional effect on delaying growth, and may avoid high initial mortality.

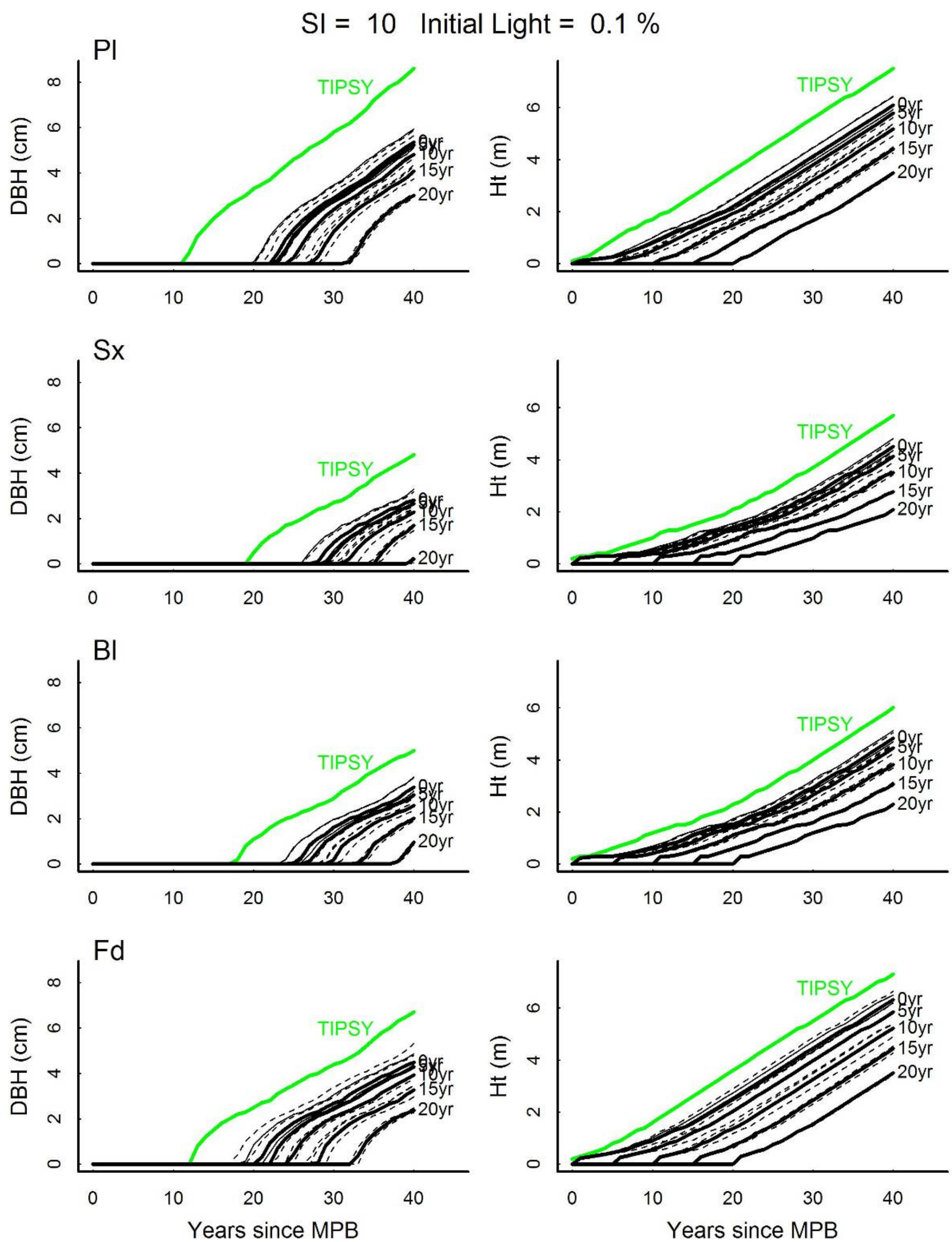
There are clearly other factors that affect when and if MPB-killed stands should be underplanted. Worker safety favours immediate planting, or delaying until the majority of snags have fallen or broken to safe heights. Immediate underplanting, in conjunction with planting of nearby salvaged blocks, would allow roads to be de-activated quickly. On the other hand, possible interactions of underplanted seedlings and the overstory snags, including mistletoe, other biological agents or even direct damage from falling snags, support delaying planting until most snags have fallen. Partial growth compensation reduces the economic cost of delaying planting, and may make delayed planting a preferred option in terms of net present value (depending on the type of stand, and the discount rate). If an alternative management option is to clear the unsalvaged MPB stands and then plant, many additional factors need to be balanced with the faster expected growth, such as costs of falling versus timber value, costs and benefits of facilitating site preparation and stand tending, and the costs and benefits of removing the MPB-killed stems for other values (wildlife habitat, hydrology, fire, etc.) The projections of growth and survival in this report are therefore just one component of decisions on how to manage unsalvaged MPB-killed stands.

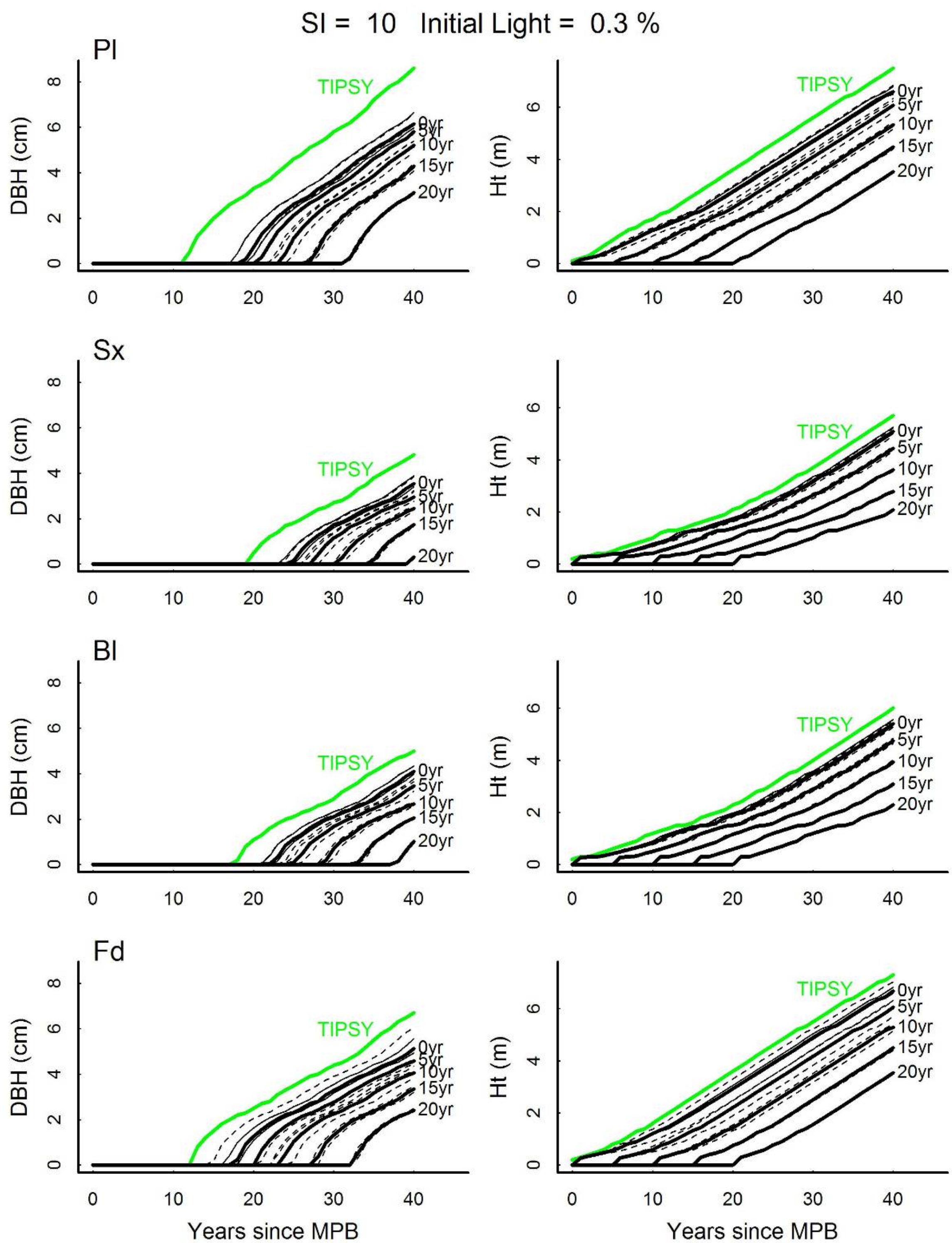
Several aspects of the underlying data – in addition to the weak survival information – should temper these results. Most of the studies reviewed for the growth-light relationships had shade from live trees (3 others were from shade cloth, 1 from MB-killed trees). In addition to shading, these live trees may also be competing with seedlings for below-ground resources, especially water. That is not the case for MPB-killed trees. To the (unknown) extent that water competition was important in some of the reviewed studies, the resulting predictions for growth delays in this report will be overstated. However, in lower-elevation, drier stands where reduced water competition due to pine mortality is likely to be most beneficial to seedlings, infill and subsequent competition from pine grass may be a complicating factor. Site preparation and wise choice of planting sites could then become an important factor in performance of underplanted seedlings. This conclusion would also apply to wetter sites where growth of shrubs after overstory mortality may cause additional local shading and competition.

These projections also do not include contributions from natural regeneration. Given the relatively gradual changes in light expected in unsalvaged post-MPB stands, advanced regeneration in the understory should have good success releasing (better than with the sudden change in a harvested stand). Underplanting would presumably be most beneficial in stands with little advanced regeneration, or when seedlings are planted to complement existing understory trees.

Confidence intervals in this report are based on the confidence intervals for the overall relationships in the previous reports. Individual studies show greater variation, due to innumerable possible factors (ecosystem type, stand conditions, seedling type, how the study was conducted, etc.) Considerable variability should be expected for individual underplanted stands, or for particular stand types. General synthesis and projections are certainly no substitute for local knowledge gained from a designed study of underplanting in different types of MPB-killed stands.

Appendix 1. Projected growth of seedlings planted under MPB-killed pure pine stands.
(See start of “Results” in text for explanation of the figures).

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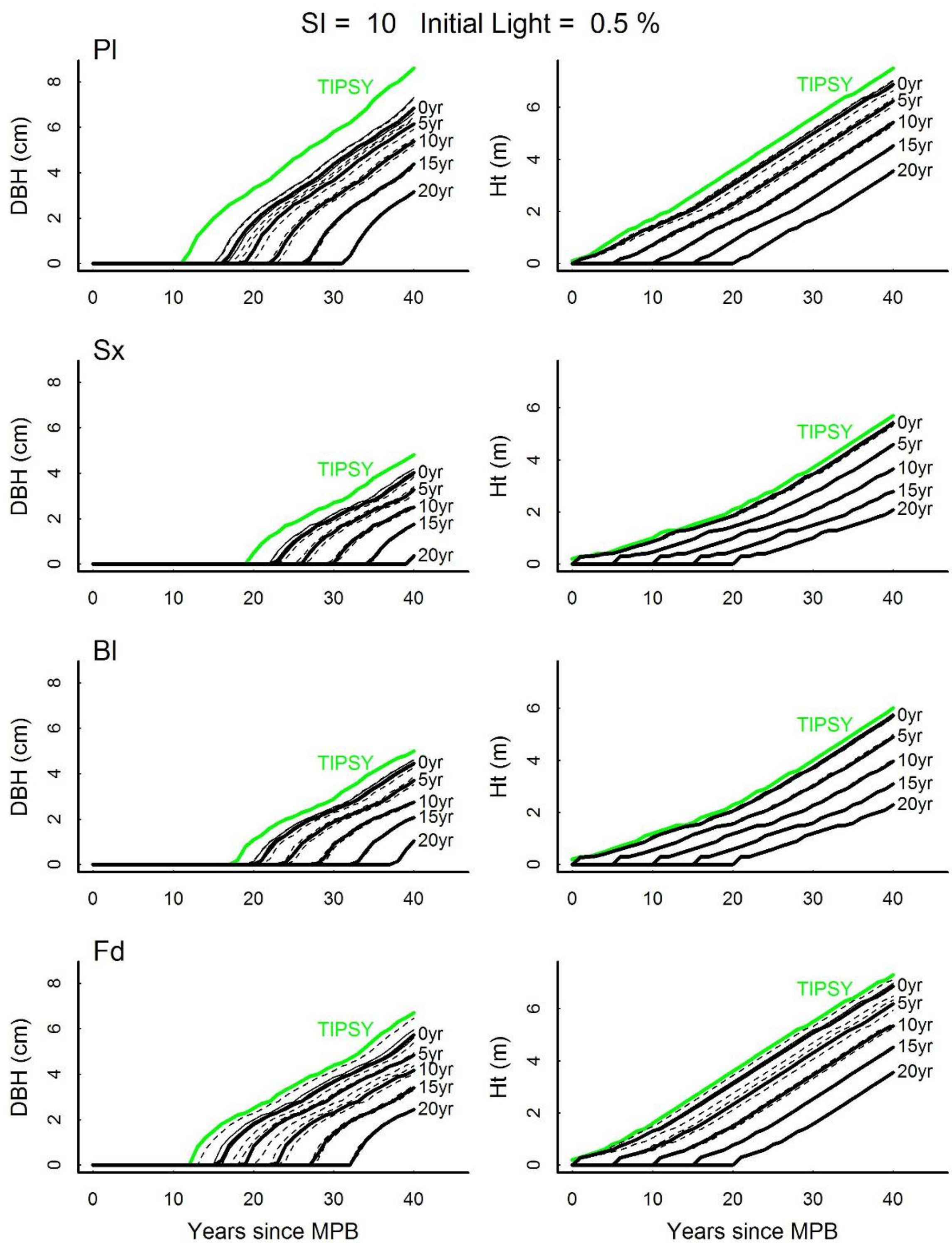
Pl
Sx
Bl
Fd
DBH (cm)
Ht (m)
TIPSY
0yr
5yr
10yr
15yr
20yr
Years since MPB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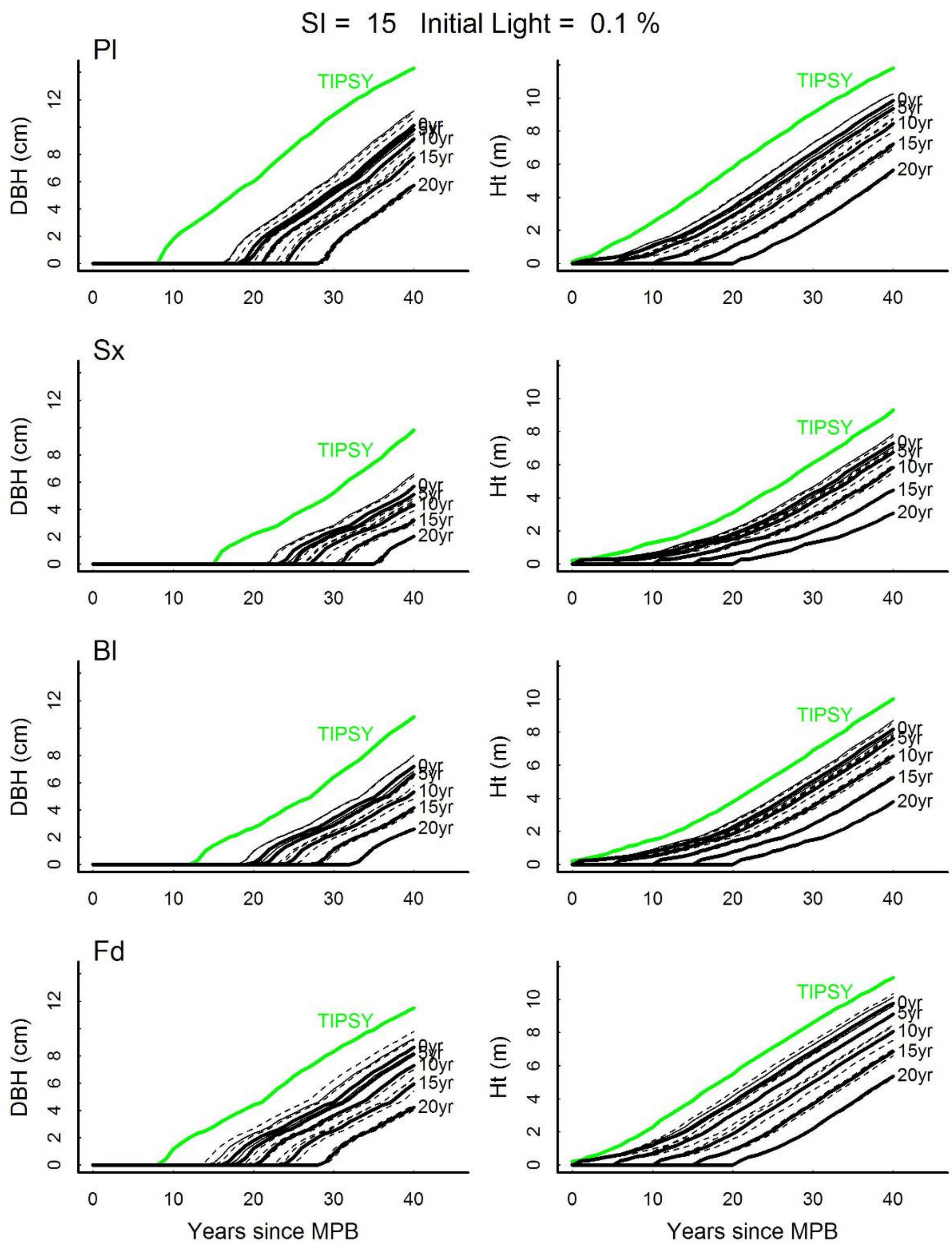
Pl
Sx
Bl
Fd
TIPSY
0yr
5yr
10yr
15yr
20yr
DBH (cm)
Ht (m)
Years since MPB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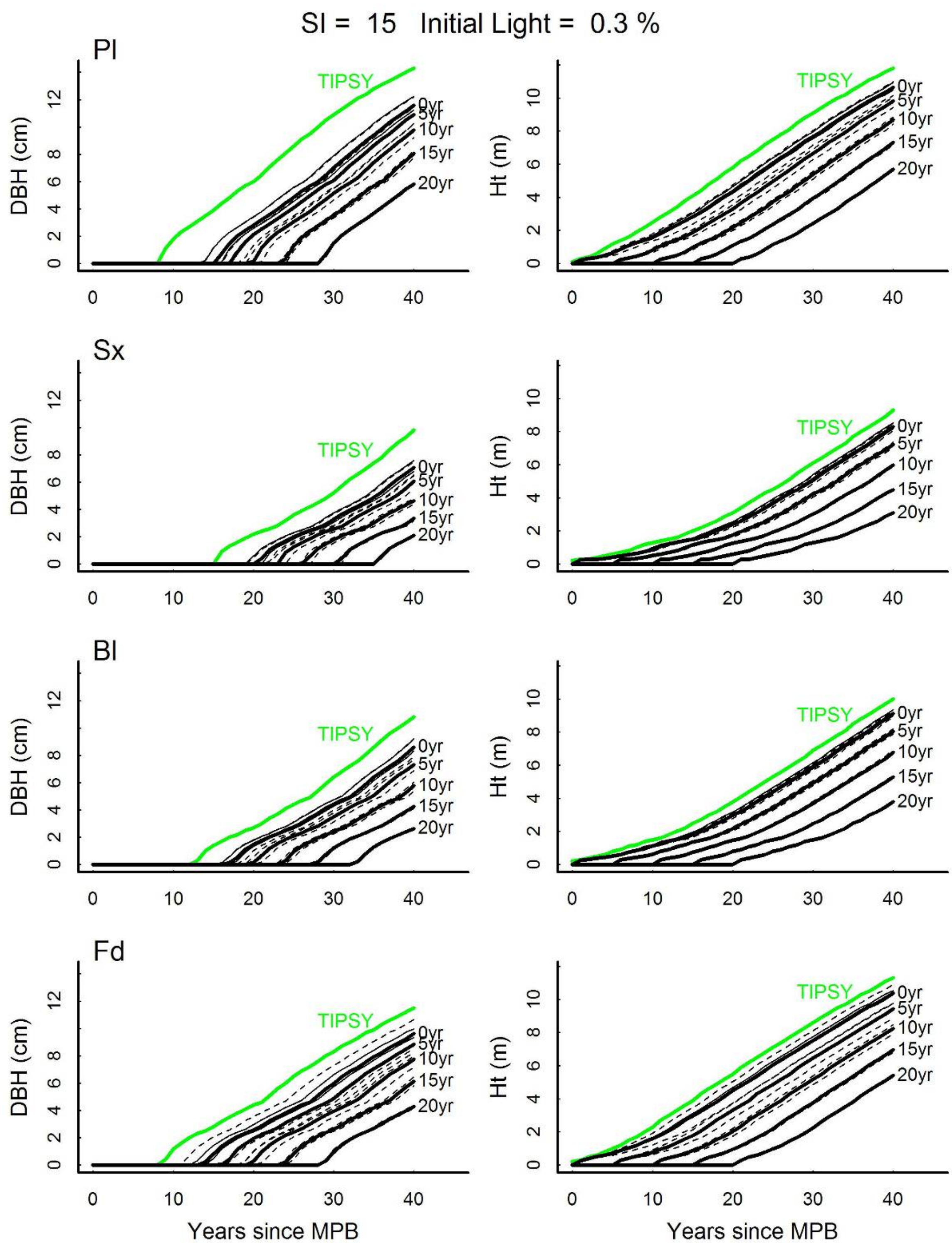
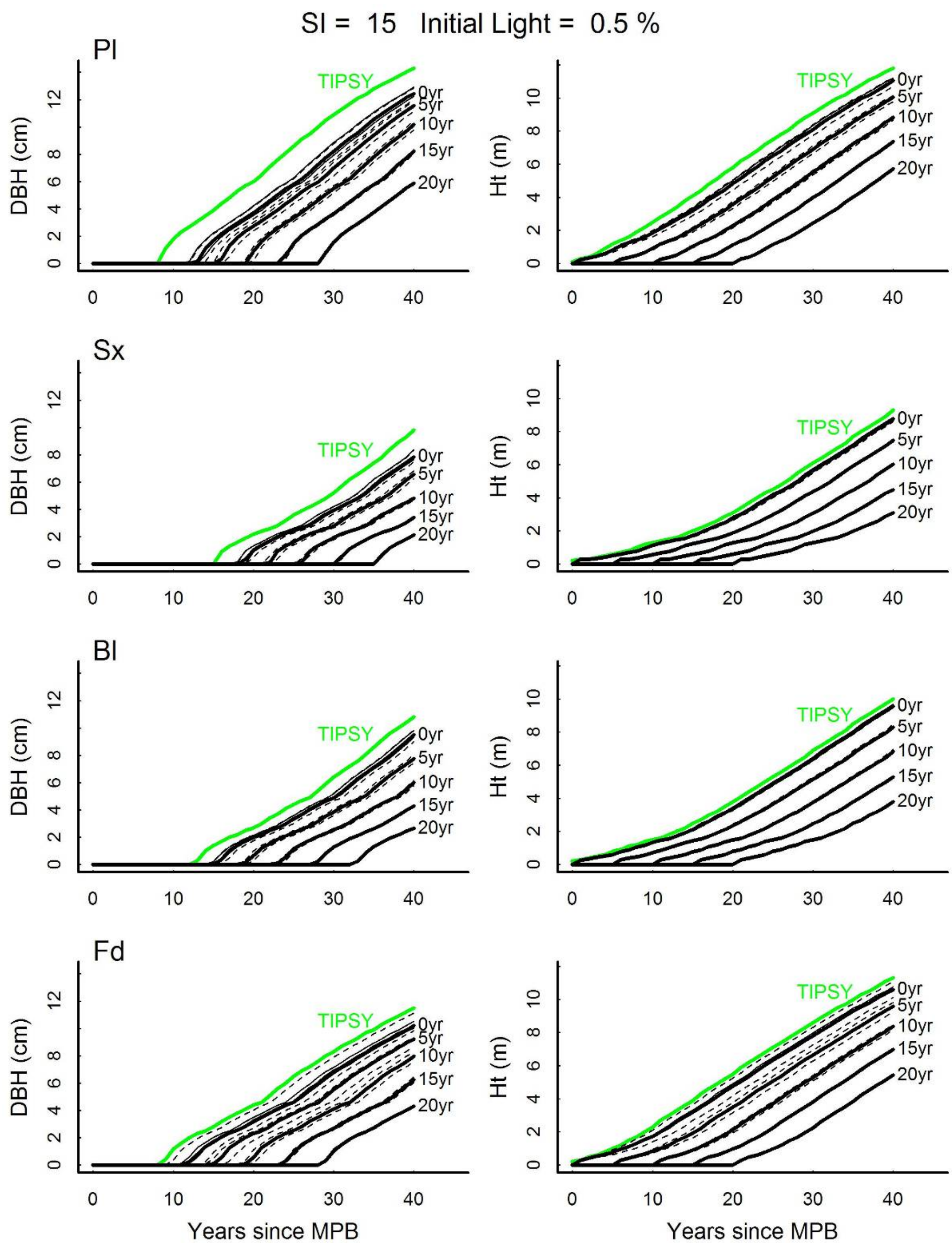
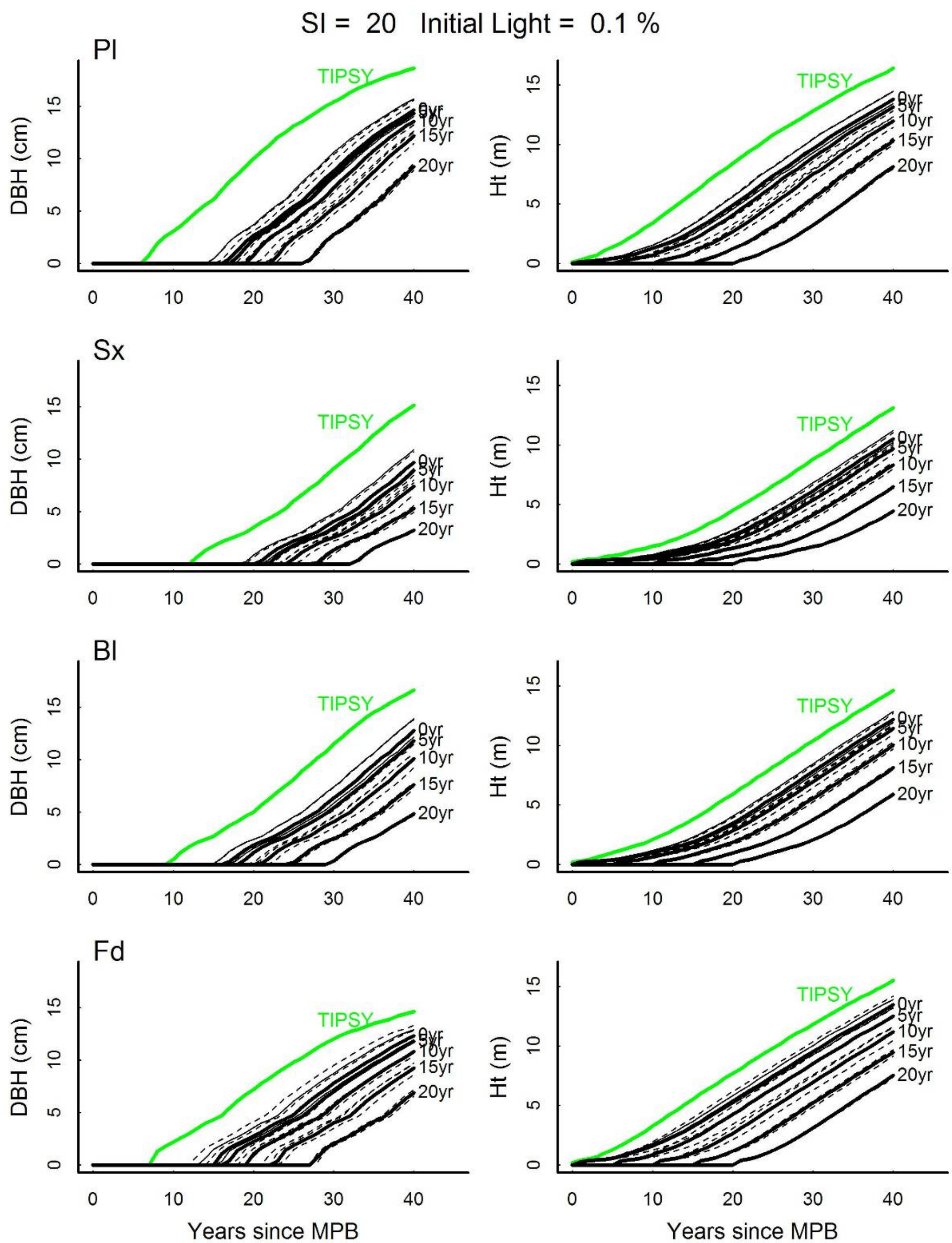
Pl
Sx
Bl
Fd
DBH (cm)
Ht (m)
TIPSY
0yr
5yr
10yr
15yr
20yr
0 10 20 30 40
Years since MPB
Years since MPB


SI = 15 Initial Light = 0.3 %
Pl
Sx
Bl
Fd
DBH (cm)
Ht (m)
TIPSY
0yr
5yr
10yr
15yr
20yr
Years since MPB


SI = 15 Initial Light = 0.5 %
Pl
Sx
Bl
Fd
DBH (cm)
Ht (m)
TIPSY
0yr
5yr
10yr
15yr
20yr
Years since MPB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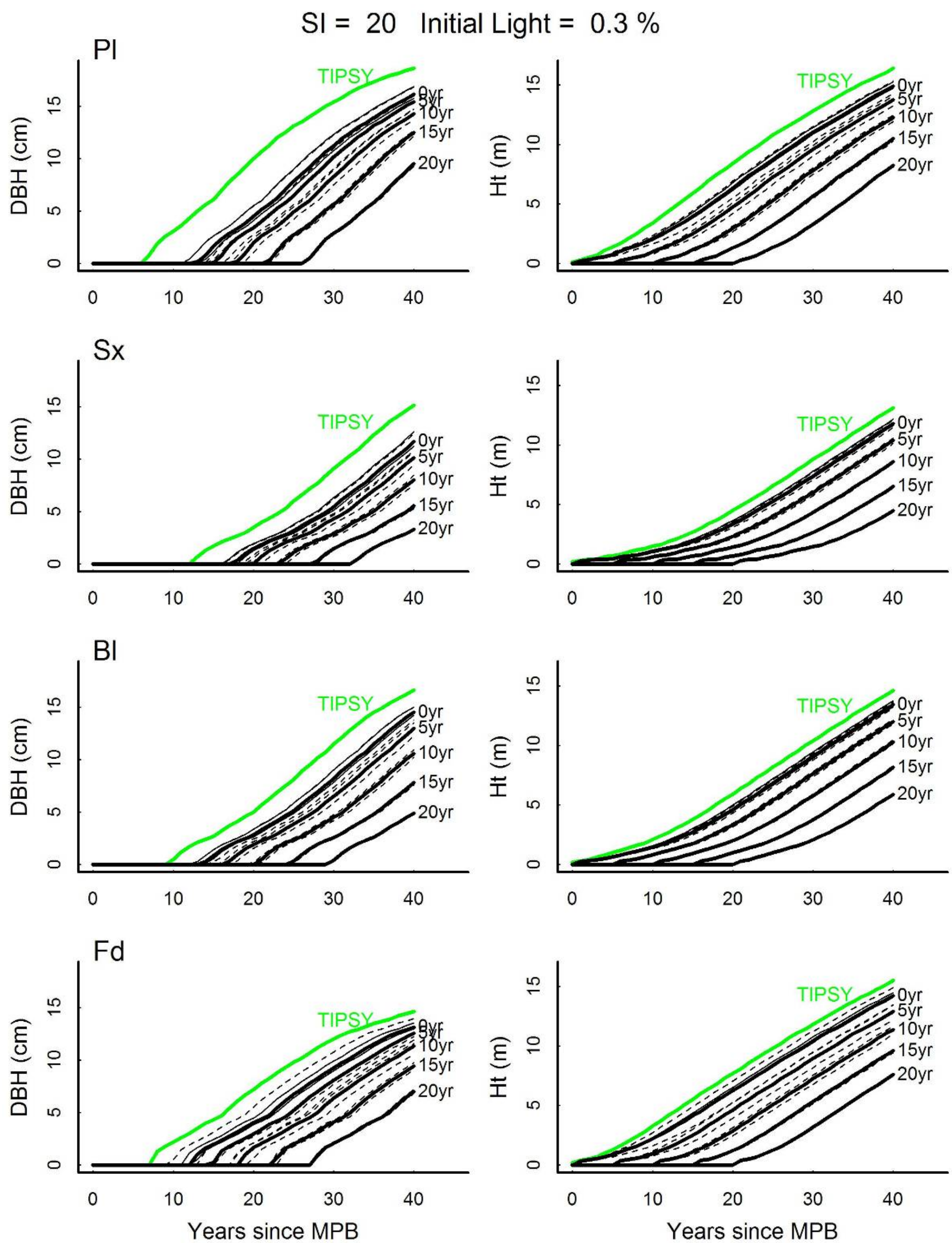
Pl
Sx
Bl
Fd
TIPSY
0yr
5yr
10yr
15yr
20yr
DBH (cm)
Ht (m)
Years since MPB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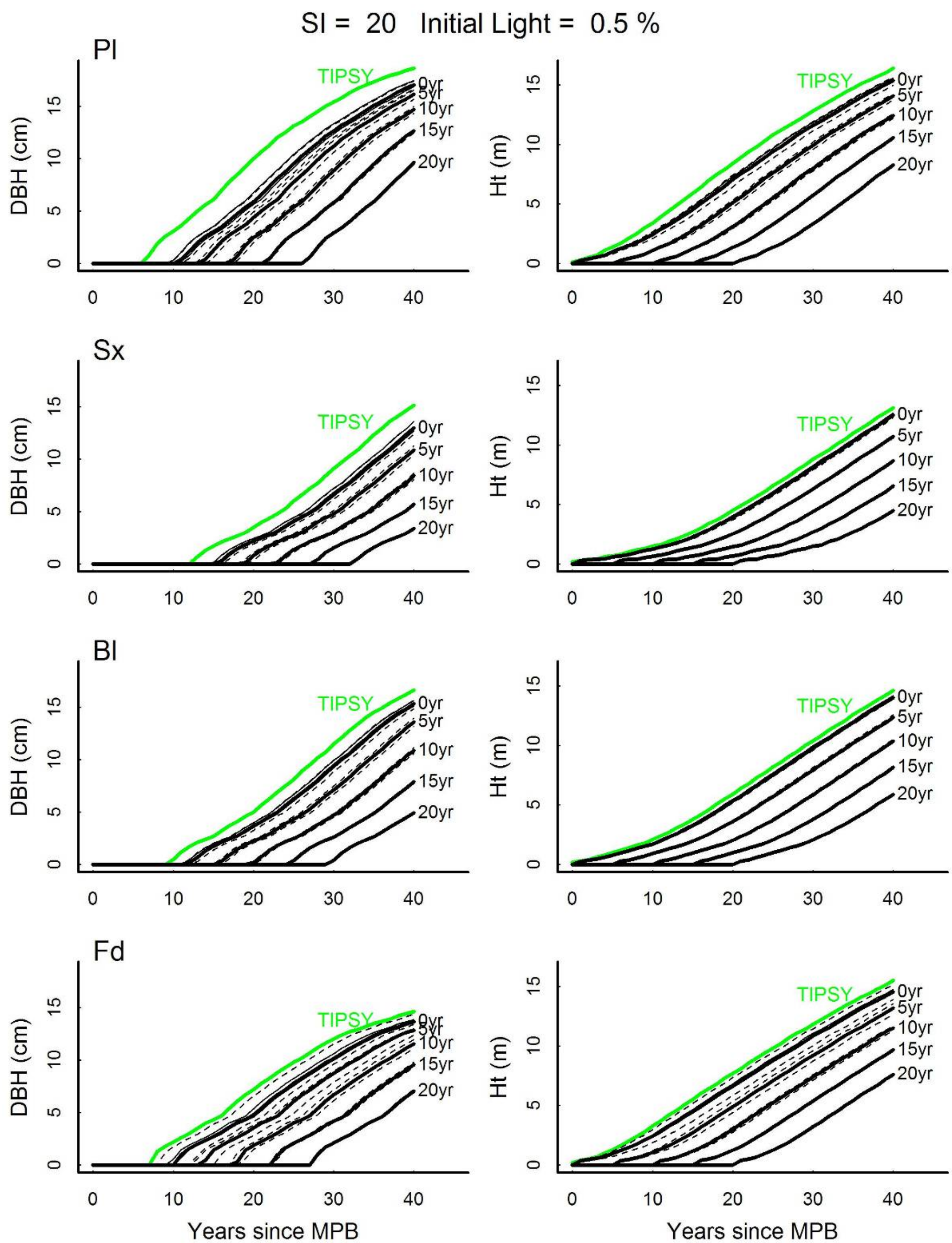
Pl
Sx
Bl
Fd
TIPSY
0yr
5yr
10yr
15yr
20yr
DBH (cm)
Ht (m)
0
5
10
15
20
30
40
Years since MPB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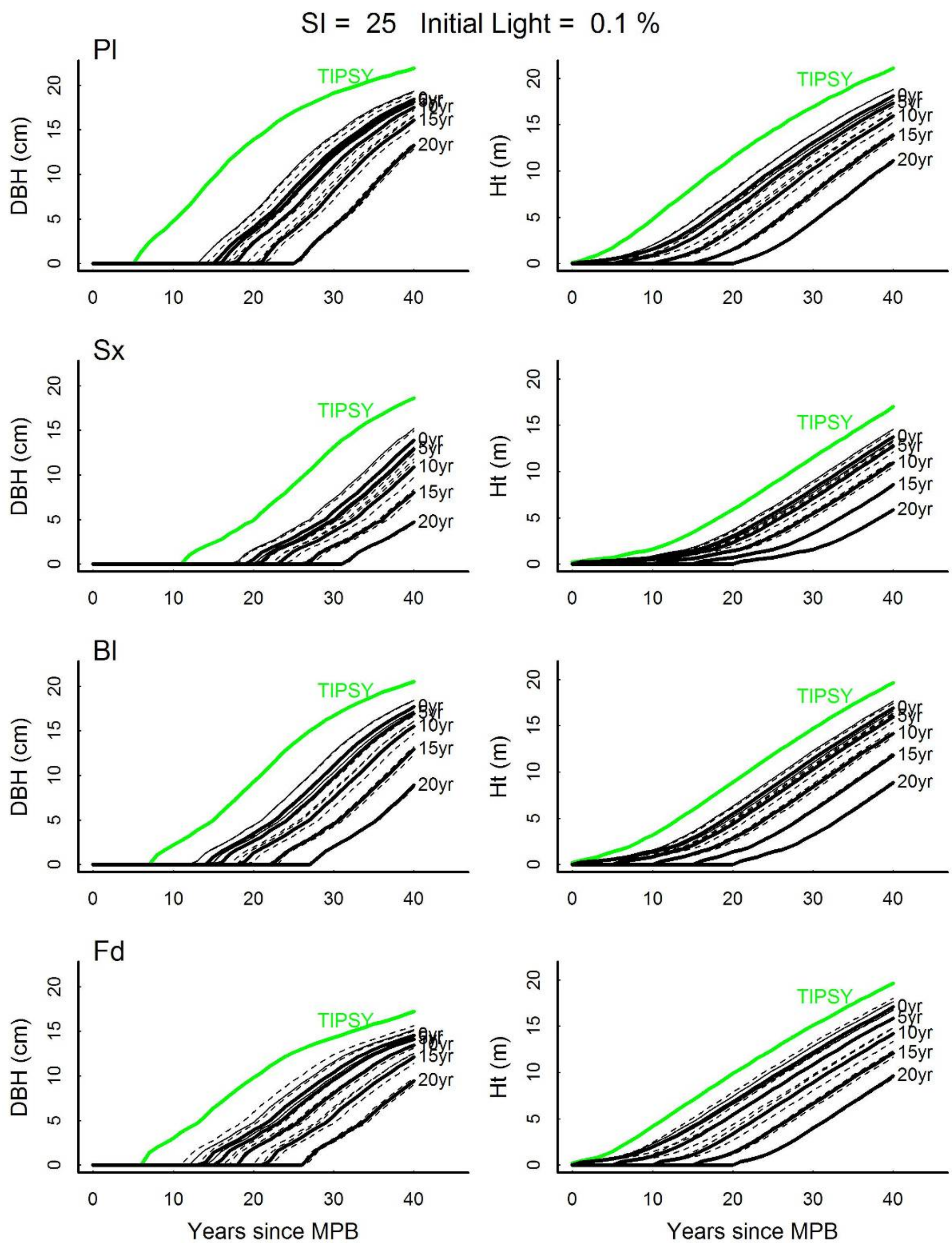
Pl
Sx
Bl
Fd
DBH (cm)
Ht (m)
TIPSY
0yr
5yr
10yr
15yr
20yr
Years since MPB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Sx
Bl
Fd
TIPSY
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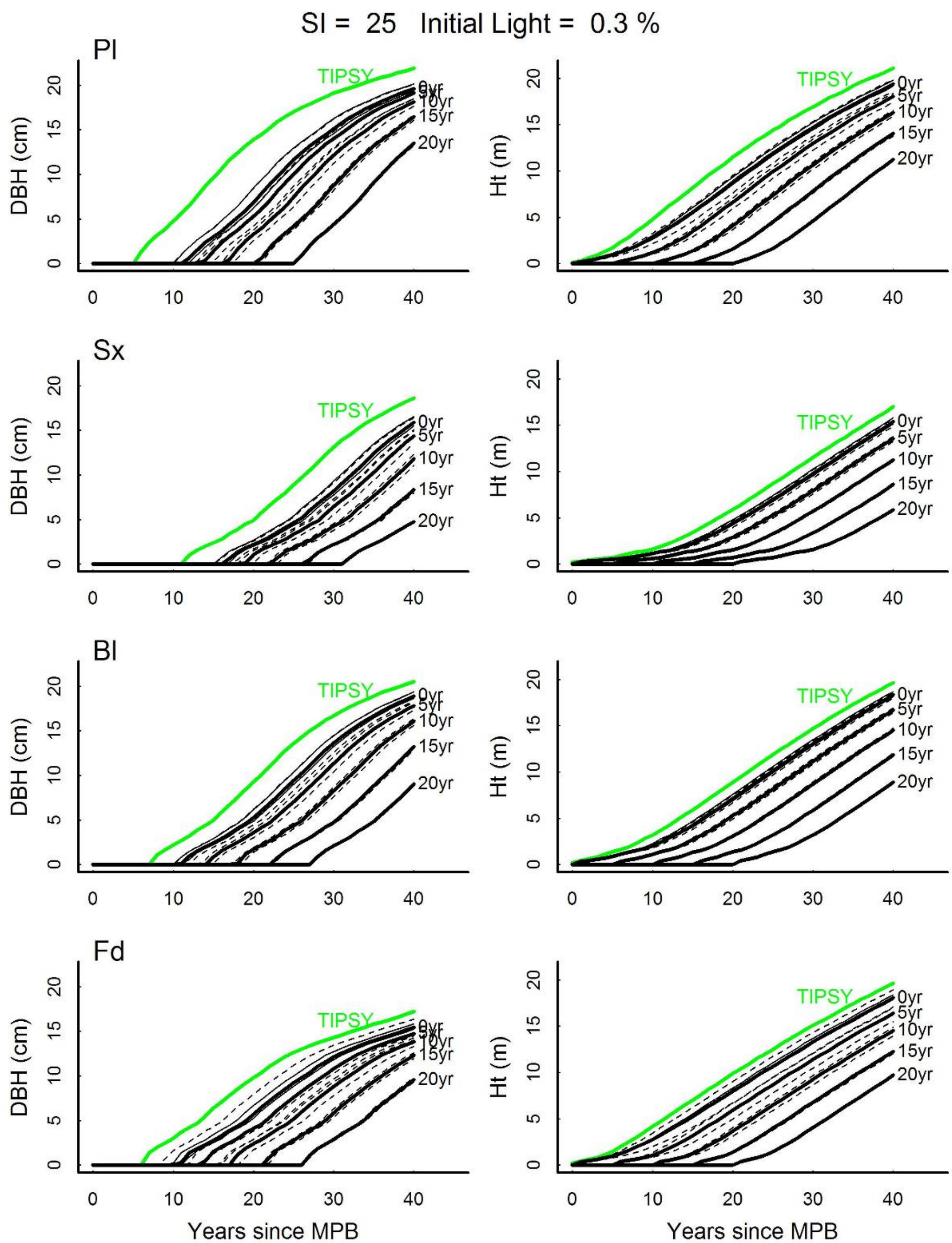
5yr
10yr
15yr
20yr
DBH (cm)
Ht (m)
Years since MPB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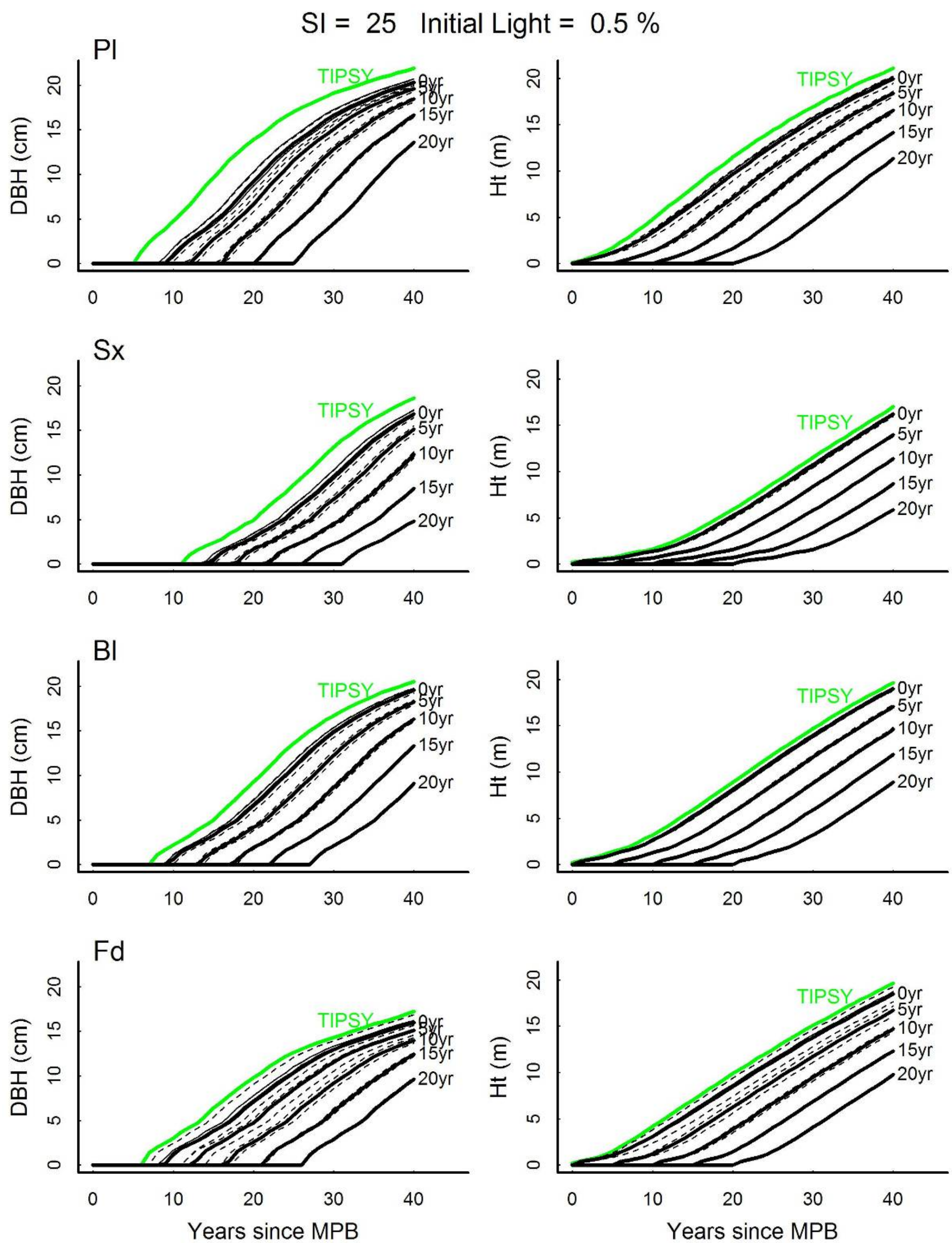
Pl
Sx
Bl
Fd
TIPSY
0yr
5yr
10yr
15yr
20yr
DBH (cm)
Ht (m)
Years since MPB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Pl
Sx
Bl
Fd
TIPSY
0yr
5yr
10yr
15yr
20yr
DBH (cm)
Ht (m)
Years since MPB

Appendix 2. Projected 5-, 10- and 20-year survival of seedlings planted under MPB-killed stands of 10, 25 and 40cm DBH, with light levels in the live stands of 10%, 30% and 50% of above-canopy light, and planting delays after MPG mortality of 0-20 years. Results are based on 3 relationships between survival and understory light levels, representing "low", "medium" and "high" ranges of the available data.

1. LOW Survival

5-year survival **CLEARCUT = 0.859**

	DBH 10cm			DBH 25cm			DBH 40cm		
Delay	**10%[1]**	**30%**	**50%**	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.113	0.429	0.528	0.059	0.409	0.505	0.048	0.396	0.499
5 years	0.464	0.591	0.712	0.391	0.512	0.636	0.346	0.491	0.607
10 years	0.662	0.766	0.810	0.531	0.676	0.760	0.494	0.628	0.737
15 years	0.832	0.852	0.863	0.781	0.823	0.847	0.751	0.812	0.836
20 years	0.858	0.867	0.869	0.827	0.852	0.860	0.810	0.841	0.856

10-year survival **CLEARCUT = 0.737**

	DBH 10cm			DBH 25cm			DBH 40cm		
Delay	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.041	0.213	0.334	0.016	0.173	0.278	0.011	0.159	0.260
5 years	0.263	0.413	0.541	0.171	0.302	0.445	0.138	0.264	0.406
10 years	0.516	0.621	0.669	0.375	0.522	0.612	0.328	0.473	0.582
15 years	0.685	0.713	0.724	0.614	0.671	0.702	0.575	0.652	0.687
20 years	0.720	0.731	0.737	0.671	0.705	0.720	0.642	0.687	0.711

20-year survival **CLEARCUT = 0.544**

	DBH 10cm			DBH 25cm			DBH 40cm		
Delay	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.018	0.121	0.209	0.005	0.079	0.157	0.003	0.065	0.138
5 years	0.169	0.280	0.375	0.095	0.190	0.297	0.070	0.160	0.264
10 years	0.357	0.439	0.476	0.239	0.352	0.424	0.199	0.311	0.397
15 years	0.487	0.509	0.520	0.413	0.465	0.495	0.370	0.441	0.477
20 years	0.517	0.526	0.530	0.471	0.500	0.515	0.431	0.476	0.500

[1] Light levels in live stand

2. MEDIUM Survival

5-year survival **CLEARCUT = 0.904**

	DBH 10cm			DBH 25cm			DBH 40cm		
Delay	**10%[1]**	**30%**	**50%**	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.153	0.603	0.707	0.074	0.580	0.688	0.059	0.566	0.682
5 years	0.643	0.752	0.815	0.561	0.695	0.778	0.501	0.674	0.763
10 years	0.790	0.845	0.872	0.709	0.798	0.841	0.674	0.773	0.828
15 years	0.887	0.900	0.907	0.854	0.881	0.897	0.837	0.874	0.890
20 years	0.904	0.910	0.912	0.884	0.900	0.906	0.872	0.893	0.903

10-year survival **CLEARCUT = 0.817**

	DBH 10cm			DBH 25cm			DBH 40cm		
Delay	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.084	0.412	0.540	0.032	0.361	0.496	0.022	0.340	0.480
5 years	0.468	0.601	0.682	0.355	0.515	0.622	0.298	0.480	0.597
10 years	0.673	0.737	0.769	0.571	0.674	0.730	0.528	0.645	0.710
15 years	0.781	0.800	0.808	0.730	0.771	0.792	0.704	0.757	0.782
20 years	0.806	0.814	0.818	0.771	0.795	0.806	0.749	0.782	0.799

20-year survival **CLEARCUT = 0.668**

	DBH 10cm			DBH 25cm			DBH 40cm		
Delay	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.052	0.287	0.399	0.016	0.226	0.344	0.010	0.202	0.322
5 years	0.350	0.466	0.536	0.245	0.381	0.476	0.196	0.347	0.450
10 years	0.528	0.585	0.614	0.426	0.521	0.573	0.381	0.489	0.552
15 years	0.624	0.641	0.650	0.563	0.605	0.630	0.527	0.586	0.615
20 years	0.648	0.654	0.657	0.610	0.634	0.645	0.577	0.614	0.634

[1] Light levels in live stand

3. HIGH Survival

5-year survival **CLEARCUT = 0.951**

	DBH 10cm			DBH 25cm			DBH 40cm		
Delay	**10%[1]**	**30%**	**50%**	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.271	0.711	0.794	0.159	0.692	0.780	0.134	0.679	0.775
5 years	0.744	0.827	0.879	0.674	0.785	0.847	0.628	0.769	0.834
10 years	0.858	0.906	0.928	0.795	0.864	0.902	0.769	0.843	0.890
15 years	0.938	0.946	0.951	0.913	0.934	0.944	0.899	0.929	0.939
20 years	0.949	0.953	0.954	0.936	0.946	0.950	0.928	0.941	0.948

10-year survival **CLEARCUT = 0.904**

	DBH 10cm			DBH 25cm			DBH 40cm		
Delay	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.181	0.552	0.668	0.092	0.504	0.627	0.070	0.483	0.613
5 years	0.605	0.723	0.796	0.497	0.646	0.739	0.444	0.614	0.716
10 years	0.785	0.842	0.869	0.699	0.787	0.837	0.661	0.761	0.819
15 years	0.877	0.891	0.896	0.839	0.870	0.885	0.817	0.860	0.878
20 years	0.894	0.900	0.903	0.870	0.887	0.894	0.855	0.878	0.890

20-year survival **CLEARCUT = 0.818**

	DBH 10cm			DBH 25cm			DBH 40cm		
Delay	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**	**10%**	**30%**	**50%**
0 years	0.135	0.449	0.567	0.059	0.378	0.508	0.043	0.348	0.484
5 years	0.518	0.633	0.703	0.402	0.549	0.643	0.347	0.513	0.616
10 years	0.693	0.749	0.775	0.597	0.688	0.738	0.554	0.657	0.719
15 years	0.782	0.796	0.802	0.732	0.768	0.787	0.701	0.752	0.776
20 years	0.801	0.806	0.808	0.772	0.790	0.799	0.746	0.775	0.790

[1] Light levels in live stand