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Site Index Comparisons for Forest Species in the Upper Great Lakes Area of the United States and Canada

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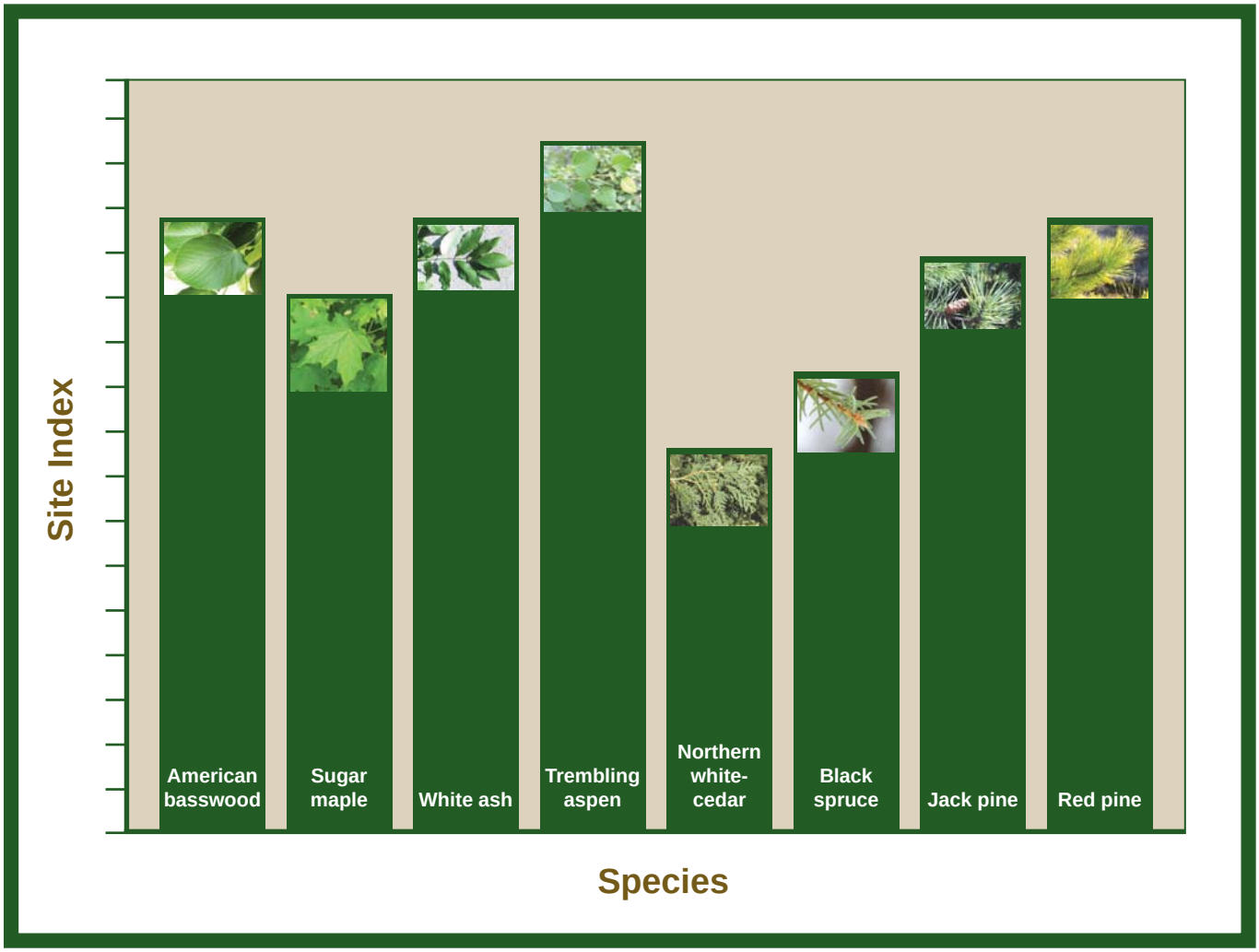

Abstract

This report summarizes six studies that compare site index relations between 24 hardwood and conifer species in the Upper Great Lakes area of the United States and Canada. These six studies have many regression models and graphs for comparing site index between forest species thus providing tools for estimating site index for alternative tree species based on direct site index measurements using tree species actually present in forest stands. Thus the objective of this summary paper is to summarize these models so that we can provide the most accurate tools available for estimating the tree species that are most productive and economically valuable for management on each forest site.

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INTRODUCTION

A key question in timber management is "What species of tree is the most productive and commercially desirable for each forest location?" Such a question is frequently encountered with stand conversion, tree planting, release, timber stand improvement, thinning, and with final harvest prescriptions. This is a critical question because for each forest location tree species may differ in site quality, rate of growth, and volume and value of yield. Some of the greatest increases in yield and value of timber are obtained when poorly stocked forest stands having slow-growing, poor quality, less commercially valuable forest species are converted to fully stocked stands having fast-growing tree species capable of rapidly producing yields of the most commercially valuable forest products. Thus forest managers need site quality and yield estimates, not only for the species of tree actually present at a forest location, but also for all alternative tree species that might be considered for future management at that location.

The question about the most productive tree species for each location could easily be answered only in the unlikely situation where all forested areas have older, even-aged, fully stocked, undisturbed mixed stands, and where all of these mixed stands contain free-growing dominant and codominant trees of each of the alternative tree species that might be considered for management on that location. Thus for these undisturbed mixed forest stands we could measure and compare the growth achieved by each of the alternative tree species. These on-the-ground measurements then would provide the evidence about which tree species is the most productive at that location. But we rarely have such fully stocked and undisturbed mixed forest stands containing free-growing dominant and codominant trees of all alternative species. Instead, we are confronted by a variety of partially cut, uneven-aged or high-graded forest stands that are not indicative of the actual productive abilities of the different tree species in these stands. This dilemma is particularly acute when we are dealing with tree species that are naturally uncommon, or that presently are uncommon due to past overcutting or high-grading because of past harvesting that removed the most valuable and merchantable tree species from the forest stand.

A desirable alternative for selecting the most productive and desirable species are species comparative trials consisting of older plantations where various alternative tree species are grown on adjacent plots of land having similar soil, topography, and site quality. The growth and yield performance of each species of tree in these trial plantations is then evidence of what tree species is most productive for that particular site.

Examples of such species comparison trials are studies by Alban (1978, 1985) and Schlaegel (1975). The 1978 Alban study was based on 25 pairs of adjacent 28- to 42-year-old red pine[1] and jack pine plantations and showed that red pine plantations had greater annual increment and greater basal area than adjacent similar aged jack pine plantations. McClain et al. (1994) and Homagain et al. (2011) also showed that red pine plantations in northwestern Ontario produced much greater yield than adjacent similar aged white and black spruce plantations.

Unfortunately we rarely have sufficient even-aged undisturbed natural stands, and we rarely have older species comparison trials that can provide the information needed for comparing growth and yield for alternative tree species. The few older species comparison trials available for representing growth and yield of alternative tree species are unlikely to represent the full range of forest sites or forest species found in a forest region.

Species site index comparisons

Therefore we must turn to alternative methods such as studies that compare site index for tree species growing together in locations similar in site quality. This method is based on the close association between site index and stand volume as reflected in normal yield tables for most of our major tree species; these tables express potential yield for pure, fully stocked stands according to stand age and site index. Thus site index comparisons between forest tree species can be considered as an alternative for the direct comparisons of volume based on undisturbed fully stocked natural stands or by plantation species comparison trials. If we know the site index value for each of the alternative species being compared, we then

[1]Scientific names for tree species are given in Appendix I.

can refer to yield tables for each of these species for comparisons of yield at various ages for specified levels of site index.

We frequently have many undisturbed even-aged natural forest stands where several tree species are growing together and where each of these tree species have free-growing dominant and codominant trees. For such stands, we can directly measure and compare site indices for each of these alternative tree species using site index curves published for each of these species (Carmean et al. 1989). Potential yield and potential commercial value then could be estimated for each of the alternative species using appropriate yield tables and models.

However many even-aged forest stands are essentially pure stands having only a single species with measurable dominant and codominant trees, e.g., pure jack pine, black spruce, or trembling aspen stands. For example, a pure even-aged jack pine stand might only have dominant and codominant jack pine trees, thus we only are able to directly estimate jack pine site index using jack pine site index curves (Carmean et al. 2001). For such pure stands, we would be uncertain about site indices for other alternative tree species such as black spruce, trembling aspen, and red pine that could be considered for management on that site. The reason is that no direct estimates of site index for these alternative species are possible simply because this stand lacks suitable dominant and codominant trees for these alternative tree species.

The species site index comparison method (Carmean 1975, 1979, 1996, Carmean and Vasilevsky 1971) uses direct site index measurements from tree species present in the stand as a means for estimating site index of alternative species not present in the stand that might be considered for management on that particular site. For example, in the pure jack pine stand described above we could directly estimate jack pine site index using height and age measurements from the dominant and codominant jack pine trees together with jack pine site index curves. We then could use models and graphs that relate measured jack pine site index to estimated site index for other alternative tree species not present in the stand. Armed with site index estimates for each of the alternative tree species, we then could refer to yield tables or yield models for estimations about which of the alternative tree species is most productive and commercially valuable tree for that location. This is accomplished for each location by ranking the estimated site index values for the various alternative species, and then by referring to yield tables and models for estimates of potential yields and product values for fully stocked stands of each of these alternative tree species. Silvicultural practices then could be considered for establishing and managing stands of the most productive and commercially desirable species of tree for each location.

Species site index comparison studies are based on research where a large number of comparison plots are located in fully stocked even-aged stands representing the wide range of soil and site conditions found in a particular area or region. Each plot should contain free-growing, uninjured dominant and codominant trees for two or more tree species thus providing paired site index observations for each of the tree species on the plot. Site index relations between these paired tree species using many comparison plots are then expressed using linear regression models and graphs that estimate site index for each of the alternative species based on direct site index measurements from the particular tree species that are actually present in the stand.

The objective of this report is to summarize results from six site index comparison studies for the Upper Great Lakes area: one study was for tree species in northern Minnesota (Carmean and Vasilevsky 1971), and another study was for northern hardwood species in northern Wisconsin and upper Michigan (Carmean 1979). An unpublished site index comparison study is available based on a Forest Resources Evaluation Program (FREP) report for Minnesota, Wisconsin, and Michigan (Carmean and Hahn 1981). Three unpublished H.B.Sc. Forestry theses also are available at Lakehead University in Thunder Bay, Ontario (Dillabough 1983, Ortiz 1985, Thurston 1984).

These six site index comparison studies have produced a large number of regression models and site index comparison graphs for 24 of the major hardwood and

conifer forest species in the Upper Great Lakes area. Several of these studies provide separate and independent models for the same paired species comparisons, thus these separate and independent models for the same species comparisons can be compared and recommendations can be given about which models are the most precise site index comparison models for use in forest stands of the Upper Great Lakes area of the United States and Canada.

THE SIX SITE INDEX COMPARISON STUDIES

Northern Minnesota

This study (Carmean and Vasilevsky 1971) was based on tree height and total age data from a large number of randomly located U.S. Forest Service, Forest Inventory and Analysis plots (hereafter referred to as forest survey plots); several U.S. Soil Conservation Service (USCS)[2] plots also were included. The forest survey plots were carefully screened to reject plots in stands that were poorly stocked, uneven-aged, or that were too young for dependable site index estimation. For our analysis, each even-aged plot had suitable dominant and codominant trees for two or more tree species so total age and total height measurements from these trees were used for estimating site index for each of the species found on the plot. Average site index (total height in feet of dominant and codominant trees at 50 years total age) for each species on each plot was estimated using harmonized site index curves (Carmean et al. 1989). Site index measurements from paired species combinations from many plots then were used to estimate linear regression models and site index comparison graphs for nine site index comparisons among conifer and hardwood tree species in northern Minnesota (Table 1).

Northern Hardwoods in Northern Wisconsin and Upper Michigan

This detailed study (Carmean 1979) was based on stem analyses from dominant and codominant trees growing in 204 carefully selected, fully stocked, even-aged, undisturbed northern hardwood plots. On each plot average height-age curves were constructed for each species using stem analyses from one to six dominant and codominant trees. Site index for each species on each plot then was estimated using average height-age curves to observe average tree height (site index) at 50 years total age. Paired site index estimates on each plot then were used to develop regression models and site index comparison graphs for 51 species site index comparison models for various northern hardwood tree species in northern Wisconsin and Upper Michigan (Table 1). These stem analysis data also were used for constructing polymorphic (many shaped) site index curves for 12 northern hardwood tree species (Carmean 1978).

The FREP Study

This unpublished study (Carmean and Hahn 1981) was similar to the earlier Carmean and Vasilevsky (1971) study but used a much greater number of forest survey and USCS plots located in Minnesota, Wisconsin, and Michigan. The randomly located forest survey plots were screened to reject plots that were poorly stocked or that had plots with trees that were uneven-aged or too young. Site index estimates again were based on harmonized site index curves (Carmean et al. 1989); site index estimation was aided using site index curve formulations developed by Lundgren and Dolid (1970). Site index estimates for paired tree species combinations then were used to develop regression models and graphs for 46 site index comparisons among conifer and hardwood tree species in Minnesota, Wisconsin, and Michigan (Table 1).

Conifers and Trembling Aspen in North Central Ontario

This unpublished H.B.Sc. Forestry thesis (Thurston 1984) was based on 101 carefully selected plots in well stocked, even-aged, undisturbed stands having mixtures of conifer species and trembling aspen. Several of these plots already had site index estimates based on stem-analysis data that had been used for polymorphic site index curve and soil-site studies in north central Ontario (Carmean 1996, 2007). But most plots used total age and total height measurements from one to four dominant and codominant trees for each tree species on each plot; site index for each species was estimated using the polymorphic site index curves for northwest Ontario

[2]Now known as Natural Resources Conservation Service.

Table 1.—Species site index comparisons between hardwood and conifer tree species are given in six studies for the Upper Great Lakes area. For each paired species combination, the number of plots and coefficients of determination (R^2) are given. Recommended models are noted with an asterisk.

Comparison number	Species compared	Carmean and Hahn (1981)	Carmean and Vasilevsky (1971)	Thurston (1984)	Ortiz (1985)	Dillabough (1983)	Carmean (1979)
1	Sugar maple-red maple	17 (0.33)	-	-	-	-	89 (0.79)*
2	Sugar maple-yellow birch	18 (0.61)	-	-	-	-	109 (0.74)*
3	Sugar maple-Am. beech	-	-	-	-	14 (0.33)	19 (0.38)*
4	Sugar maple-Am. basswood	159 (0.51)	-	-	-	23 (0.68)	109 (0.71)*
5	Sugar maple-Am. elm	15 (0.76)	-	-	-	-	94 (0.74)*
6	Sugar maple-white ash	41 (0.40)	-	-	-	52 (0.37)	59 (0.69)*
7	Sugar maple-black ash	9 (0.40)	-	-	-	-	27 (0.60)*
8	Sugar maple-n. red oak	77 (0.42)	-	-	-	16 (0.62)	26 (0.44)*
9	Sugar maple-white birch	-	-	-	-	-	23 (0.59)*
10	Sugar maple-aspens	79 (0.30)	-	-	-	-	7 (0.61)*
11	Sugar maple-bigtooth aspen	13 (0.61)*	-	-	-	-	-
12	Sugar maple-black cherry	-	-	-	-	27 (0.32)	36 (0.73)*
13	Sugar maple-bitternut hickory	-	-	-	-	16 (0.64)*	-
14	Red maple-yellow birch	12 (0.32)	-	-	-	-	71 (0.70)*
15	Red maple-Am. beech	-	-	-	-	-	13 (0.38)*
16	Red maple-Am. basswood	-	-	-	-	-	45 (0.79)*
17	Red maple-Am. elm	-	-	-	-	-	39 (0.56)*
18	Red maple-white ash	14 (0.56)	-	-	-	-	30 (0.63)*
19	Red maple-black ash	-	-	-	-	-	19 (0.60)*
20	Red maple-n. red oak	33 (0.29)	-	-	-	-	23 (0.72)*
21	Red maple-black cherry	-	-	-	-	-	33 (0.58)*
22	Red maple-white birch	10 (0.36)	-	-	-	-	16 (0.67)*
23	Red maple-aspens	51 (0.31)	-	-	-	-	8 (0.80)*
24	Yellow birch-Am. beech	-	-	-	-	-	15 (0.43)*
25	Yellow birch-Am. basswood	10 (0.40)	-	-	-	-	70 (0.78)*
26	Yellow birch-Am. elm	-	-	-	-	-	60 (0.78)*
27	Yellow birch-white ash	-	-	-	-	-	37 (0.68)*
28	Yellow birch-black ash	-	-	-	-	-	20 (0.61)*
29	Yellow birch-n. red oak	-	-	-	-	-	14 (0.74)*
30	Yellow birch-black cherry	-	-	-	-	-	25 (0.61)*
31	Yellow birch-white birch	-	-	-	-	-	16 (0.73)*
32	Yellow birch-aspens	-	-	-	-	-	7 (0.89)*
33	Am. basswood-Am. elm	22 (0.70)	-	-	-	-	86 (0.70)*
34	Am. basswood-white ash	-	-	-	-	33 (0.47)	64 (0.70)*
35	Am. basswood-black ash	10 (0.49)	-	-	-	-	31 (0.63)*
36	Am. basswood-n. red oak	-	-	-	-	13 (0.59)	29 (0.76)*
37	Am. basswood-black cherry	-	-	-	-	11 (0.58)	15 (0.68)*
38	Am. basswood-white birch	14 (0.76)	-	-	-	-	20 (0.67)*
39	Am. basswood-aspens	85 (0.33)	-	-	-	-	8 (0.72)*
40	Am. basswood-trembling aspen	68 (0.35)	16 (0.45)*	-	-	-	-
41	Am. elm-white ash	-	-	-	-	-	51 (0.78)*
42	Am. elm-black ash	17 (0.58)	-	-	-	-	34 (0.65)*
43	Am. elm-n. red oak	-	-	-	-	-	15 (0.39)*

continued

Table 1.—continued

Comparison number	Species compared	Carmean and Hahn (1981)	Carmean and Vasilevsky (1971)	Thurston (1984)	Ortiz (1985)	Dillabough (1983)	Carmean (1979)
44	Am. elm-black cherry	-	-	-	-	-	16 (0.78)*
45	Am. elm-white birch	-	-	-	-	-	12 (0.71)*
46	Am. elm-aspens	-	-	-	-	-	7 (0.83)*
47	White ash-black ash	-	-	-	-	-	27 (0.75)*
48	White ash-n. red oak	42 (0.48)	-	-	-	24 (0.55)	22 (0.77)*
49	White ash-white birch	-	-	-	-	-	9 (0.69)*
50	White ash-aspens	-	-	-	-	-	7 (0.85)*
51	Black ash-n. red oak	-	-	-	-	-	10 (0.51)*
52	Black ash-balsam poplar	8 (0.49)*	-	-	-	-	-
53	N. red oak-white oak	37 (0.77)*	-	-	-	-	-
54	N. red oak-trembling aspen	106 (0.48)*	-	-	-	-	-
55	N. red oak-bigtooth aspen	58 (0.55)*	-	-	-	-	-
56	N. red oak-aspens	164 (0.53)	-	-	-	-	7 (0.59)*
57	N. red oak-white birch	-	32 (0.44)	-	-	-	15 (0.63)*
58	White birch-trembling aspen	267 (0.37)	106 (0.51)*	-	-	-	-
59	White birch-bigtooth aspen	25 (0.61)*	-	-	-	-	-
60	White birch-aspens	292 (0.39)	-	-	-	-	7 (0.91)*
61	Trembling aspen-bigtooth aspen	25 (0.83)*	-	-	-	-	-
62	Trembling aspen-balsam poplar	122 (0.51)*	-	-	-	-	-
63	Black cherry-bitternut hickory	-	-	-	-	11 (0.68)*	-
64[a]	Jack pine-red pine	48 (0.63)*	66 (0.40)	-	-	-	-
65	Jack pine-black spruce	-	-	57 (0.66)	39 (0.80)*	-	-
66	Jack pine-tamarack	-	-	6 (0.60)*	-	-	-
67	Jack pine-trembling aspen	80 (0.32)	-	35 (0.33)	26 (0.69)*	-	-
68	Jack pine-white birch	7 (0.62)*	-	-	-	-	-
69[a]	Red pine-white pine	77(0.70)*	58 (0.47)	-	-	58 (0.55)	-
70	Red pine-white spruce	8 (0.44)	15 (0.65)*	-	-	11 (0.56)	-
71	Red pine-red maple	8 (0.61)*	-	-	-	-	-
72	White pine-white spruce	-	23 (0.62)	-	-	23 (0.71)*	-
73	White pine-trembling aspen	14 (0.72)*	-	-	-	-	-
74	White pine-red maple	10 (0.46)*	-	-	-	-	-
75	Black spruce-tamarack	26 (0.34)	67 (0.52)	9 (0.91)*	-	-	-
76	Black spruce-trembling aspen	-	-	16 (0.27)	19 (0.74)*	-	-
77	White spruce-n. white cedar	9 (0.84)*	-	-	-	-	-
78	White spruce-trembling aspen	28 (0.42)*	-	-	-	-	-
79	White spruce-Norway spruce	-	-	-	-	23 (0.76)*	-
80	Balsam fir-n. white cedar	15 (0.71)*	19 (0.43)	-	-	-	-
81	Balsam fir-white birch	15 (0.68)*	-	-	-	-	-
82	Tamarack-n. white cedar	10 (0.67)*	-	-	-	-	-

[a] Data from USCS plots located in Minnesota, Wisconsin, and Michigan.

(Carmean 1996, 2007). Paired site index estimates for tree species on each of these 51 plots then were used to estimate linear regression models and graphs for five site index comparisons among conifer species and trembling aspen in north central Ontario (Table 1).

Conifers and Trembling Aspen in Northwestern Ontario

This unpublished H.B.Sc. Forestry thesis (Ortiz 1985) was based on 84 carefully selected plots in well stocked, even-aged, undisturbed stands having mixtures of conifer species and trembling aspen. Total age and total height measurements were taken from at least three dominant and codominant trees for each tree species on each plot and were used for estimating site index using polymorphic site index curves for northwest Ontario (Carmean 1996, 2007). Paired site index estimates from each of the 84 plots then were used to develop linear regression models and graphs for three site index comparisons between conifer species and trembling aspen in northwest Ontario (Table 1).

Northern Hardwoods and Conifers in Southern Ontario

This unpublished H.B.Sc. Forestry thesis (Dillabough 1983) was based on 310 carefully selected plots in well stocked, even-aged, undisturbed hardwood stands and in older conifer plantations. Total age and total height measurements taken from at least two dominant and codominant trees for each species of tree on each plot were used for site index estimation. Site index estimation for the hardwood species was based on polymorphic site index curves for northern Wisconsin and Upper Michigan (Carmean 1978), and site index estimation for the conifer species was based on polymorphic site index curves for northwest Ontario (Carmean 1996, 2007). Paired site index estimates for each of the tree species on each of the 310 plots then were used to develop regression models and graphs for 15 site index comparisons between hardwood and conifer tree species in southern Ontario (Table 1).

ANALYSIS

Methods used for computing the site-index estimation models (Table 2) were similar for each of the six separate studies. For example, the northern hardwood study (Carmean 1979) had 89 plots for comparing site indices between sugar maple and red maple (Table 2—comparison 1). Two regression models were computed: one model used site index observations of sugar maple as the dependent variable and the other model used site index observations of red maple as the dependent variable. Both of these regression models had excellent precision (R^2 = 0.79) and there was no apparent reason to favor one model over the other. However, an additional model also was desired that could be solved forward and backward, so a third graphically constructed model was produced that averaged the trends produced by the first two models. These graphically constructed average models are given for all comparisons (Table 2), and these are the models used for computing all site index prediction graphs (Figure 1).

For each species pair, the graphically constructed average model was obtained by graphing the trends produced by each of the two regression models. For species comparison pairs having excellent precision (large R^2 values), the trend graphs based on the two models were very similar. However, for species comparison pairs that were less precise (smaller R^2 values), the two-trend graphs varied widely at the extremes of very high or very poor site index even though the two-trend graphs coincided at average site index. The graphically constructed average trend graph was obtained by graphing an average line between the two computed trend lines. Two limitations were observed for this graphically plotted line: (i) the graphed line was not extrapolated beyond actual observed site index values; and (ii) the graphically constructed line was only used when site index differences between the two computed regression lines were less than 5 feet.

Table 2.—Recommended regression models for 82 site index comparisons between hardwood and conifer species in the Upper Great Lakes area. For each comparison, the first two listed models are the computed models and the third listed model is the average model that was used from constructing the graphs in Figure 1. For 10 comparisons, improved precision was attained when a variable expressing drainage was added to the model (e.g., 1a, 2a, …).

Comp. no.	Species compared	Study†	No. of plots	SI range (ft.)	Models	Coeff. of determ. (R^2)	Std. error of estimate (%)
1	Sugar maple	6	89	42-74	$SI_{SM} = 3.336 + 0.930\ (SI_{RM})$	0.79	3.14
	vs. red maple		89	42-73	$SI_{SM} = 9.362 + 0.851\ (SI_{SM})$	0.79	3.00
					$SI_{SM} = -3.563 + 1.048\ (SI_{RM})$		
1a§					$SI_{SM} = -0.204 + 0.948\ (SI_{RM}) + 0.700\ (dr)$	0.81	3.04
					$SI_{RM} = 11.933 + 0.852\ (SI_{SM}) - 0.730\ (dr)$	0.81	2.88
					$SI_{SM} = -6.778 + 1.055\ (SI_{RM}) + 0.715\ (dr)$		
2	Sugar maple	6	109	42-75	$SI_{SM} = 6.787 + 0.885\ (SI_{YB})$	0.74	3.66
	vs. yellow birch		109	40-76	$SI_{YB} = 10.327 + 0.825\ (SI_{SM})$	0.74	3.63
					$SI_{SM} = -2.119 + 1.036\ (SI_{YB})$		
2a§					$SI_{SM} = 4.016 + 0.892\ (SI_{YB}) + 0.661\ (dr)$	0.74	3.60
					$SI_{YB} = 12.389 + 0.829\ (SI_{SM}) - 0.663\ (dr)$	0.74	3.47
					$SI_{SM} = -4.775 + 1.037\ (SI_{YB}) + 0.662\ (dr)$		
3	Sugar maple	6	19	47-65	$SI_{SM} = 25.063 + 0.611\ (SI_{B})$	0.38	3.66
	vs. Am. beech		19	45-61	$SI_{B} = 17.057 + 0.628\ (SI_{SM})$	0.38	3.91
					$SI_{SM} = 4.902 + 0.989\ (SI_{B})$		
4	Sugar maple	6	109	42-75	$SI_{SM} = 6.299 + 0.832\ (SI_{AB})$	0.68	3.77
	vs. Am. basswood		109	45-80	$SI_{AB} = 15.101 + 0.821\ (SI_{SM})$	0.68	3.74
					$SI_{SM} = -4.970 + 1.008\ (SI_{AB})$		
4a§					$SI_{SM} = 2.136 + 0.839\ (SI_{AB}) + 1.141\ (dr)$	0.71	3.61
					$SI_{AB} = 17.229 + 0.842\ (SI_{SM}) - 1.042\ (dr)$	0.71	3.62
					$SI_{SM} = -8.299 + 1.000\ (SI_{AB}) + 1.092\ (dr)$		
5	Sugar maple	6	94	43-75	$SI_{SM} = 10.609 + 0.766\ (SI_{AE})$	0.74	3.52
	vs. Am. elm		94	47-81	$SI_{AE} = 8.840 + 0.925\ (SI_{SM})$	0.74	3.87
					$SI_{SM} = 1.262 + 0.912\ (SI_{AE})$		
5a§					$SI_{SM} = 8.466 + 0.750\ (SI_{AE}) + 1.028\ (dr)$	0.74	3.37
					$SI_{AE} = 9.334 + 0.957\ (SI_{SM}) - 0.778\ (dr)$	0.72	3.81
					$SI_{SM} = 0.820 + 0.874\ (SI_{AE}) + 0.903\ (dr)$		
6	Sugar maple	6	59	42-75	$SI_{SM} = 11.189 + 0.728\ (SI_{WA})$	0.69	3.88
	vs. white ash		59	46-84	$SI_{WA} = 10.572 + 0.941\ (SI_{SM})$	0.69	4.41
					$SI_{SM} = 1.006 + 0.880\ (SI_{WA})$		
7	Sugar maple	6	27	42-70	$SI_{SM} = 7.706 + 0.801\ (SI_{BA})$	0.60	4.48
	vs. black ash		27	52-78	$SI_{BA} = 20.285 + 0.743\ (SI_{SM})$	0.60	4.31
					$SI_{SM} = -7.746 + 1.041\ (SI_{BA})$		
8	Sugar maple	6	26	42-70	$SI_{SM} = 0.906 + 0.885\ (SI_{NRO})$	0.44	4.23
	vs. n. red oak		26	57-72	$SI_{NRO} = 35.432 + 0.493\ (SI_{SM})$	0.44	3.16
					$SI_{SM} = -25.774 + 1.304\ (SI_{NRO})$		
9	Sugar maple	6	23	43-69	$SI_{SM} = 6.306 + 0.809\ (SI_{WB})$	0.59	4.24
	vs. white birch		23	47-72	$SI_{WB} = 21.018 + 0.726\ (SI_{SM})$	0.59	4.24
					$SI_{SM} = -8.975 + 1.055\ (SI_{WB})$		
10	Sugar maple	6	7	42-75	$SI_{SM} = 2.624 + 0.780\ (S_{IA})$	0.61	7.82
	vs. aspens		7	65-85	$SI_{A} = 25.430 + 0.776\ (SI_{SM})$	0.61	7.81
					$SI_{SM} = -12.575 + 0.998\ (SI_{A})$		

continued

Table 2.—continued

Comp. no.	Species compared	Study†	No. of plots	SI range (ft.)	Models	Coeff. of determ. (R^2)	Std. error of estimate (%)
11	Sugar maple	1	13	44-67	$SI_{SM} = 18.35 + 0.56\ (SI_{BA})$	0.61	5.1
	vs. bigtooth aspen		13	47-91	$SI_{BA} = 4.09 + 1.14\ (SI_{SM})$	0.61	7.3
					$SI_{SM} = 8.19 + 0.71\ (SI_{BA})$		
12	Sugar maple	6	36	42-68	$SI_{SM} = 14.384 + 0.729\ (SI_{BC})$	0.73	3.22
	vs. black cherry		36	47-73	$SI_{BC} = 2.176 + 1.000\ (SI_{SM})$	0.73	3.77
					$SI_{SM} = 6.752 + 0.854\ (SI_{BC})$		
13	Sugar maple	5	16	54-98	$SI_{SM} = 13.10 + 0.80\ (SI_{BH})$	0.64	11.2
	vs. bitternut hickory		16	62-99	$SI_{BH} = 17.43 + 0.80\ (SI_{SM})$	0.64	11.2
					$SI_{BH} = 1.66 + 1.01\ (SI_{SM})$		
14	Red maple	6	71	42-73	$SI_{RM} = 7.837 + 0.876\ (SI_{YB})$	0.70	3.60
	vs. yellow birch		71	40-72	$SI_{YS} = 10.943 + 0.802\ (SI_{RM})$	0.70	3.44
					$SI_{RM} = -2.119 + 1.048\ (SI_{YB})$		
15	Red maple	6	13	50-63	$SI_{RM} = 28.555 + 0.547\ (SI_{B})$	0.38	3.47
	vs. Am. beech		13	45-60	$SI_{B} = 13.616 + 0.688\ (SI_{RM})$	0.38	3.89
					$SI_{RM} = 9.510 + 0.904\ (SI_{B})$		
16	Red maple	6	45	43-72	$SI_{RM} = 4.068 + 0.881\ (SI_{AB})$	0.79	3.40
	vs. Am. basswood		45	45-74	$SI_{AB} = 9.417 + 0.892\ (SI_{RM})$	0.79	3.42
					$SI_{RM} = -2.628 + 0.991\ (SI_{AB})$		
17	Red maple	6	39	46-71	$SI_{RM} = 19.926 + 0.628\ (SI_{AE})$	0.56	4.09
	vs. Am. elm		39	47-76	$SI_{AE} = 8.686 + 0.899\ (SI_{RM})$	0.56	4.90
					$SI_{RM} = 6.729 + 0.844\ (SI_{AE})$		
18	Red maple	6	30	46-70	$SI_{RM} = 21.977 + 0.593\ (SI_{WA})$	0.63	4.02
	vs. white ash		30	44-76	$SI_{WA} = 0.017 + 1.065\ (SI_{RM})$	0.63	5.39
					$SI_{RM} = 11.937 + 0.751\ (SI_{WA})$		
19	Red maple	6	19	43-68	$SI_{RM} = 5.616 + 0.870\ (SI_{BA})$	0.60	4.42
	vs. black ash		19	51-70	$SI_{BA} = 20.283 + 0.688\ (SI_{RM})$	0.60	3.93
					$SI_{RM} = -9.376 + 1.119\ (SI_{BA})$		
20	Red maple	6	23	46-72	$SI_{RM} = -1.339 + 0.951\ (SI_{NRO})$	0.72	3.79
	vs. n. red oak		23	50-74	$SI_{NRO} = 18.470 + 0.760\ (SI_{RM})$	0.72	3.39
					$SI_{RM} = -11.597 + 1.114\ (SI_{NRO})$		
21	Red maple	6	33	42-72	$SI_{RM} = 19.203 + 0.655\ (SI_{BC})$	0.58	4.33
	vs. black cherry		33	42-73	$SI_{BC} = 8.391 + 0.889\ (SI_{RM})$	0.58	5.05
					$SI_{RM} = 6.478 + 0.864\ (SI_{BC})$		
22	Red maple	6	16	46-72	$SI_{RM} = -3.591 + 0.999\ (SI_{WB})$	0.67	4.75
	vs. white birch		16	47-70	$SI_{WB} = 21.976 + 0.675\ (SI_{RM})$	0.67	3.90
					$SI_{RM} = -16.538 + 1.215\ (SI_{WB})$		
23	Red maple	6	8	46-70	$SI_{RM} = -11.216 + 1.047\ (SI_{A})$	0.80	4.01
	vs. aspens		8	53-75	$SI_{A} = 21.133 + 0.766\ (SI_{RM})$	0.80	3.44
					$SI_{RM} = -18.897 + 1.168\ (SI_{A})$		
24	Yellow birch	6	15	51-65	$SI_{YB} = 25.611 + 0.614\ (SI_{B})$	0.43	2.80
	vs. Am. beech		15	48-61	$SI_{B} = 12.459 + 0.703\ (SI_{YB})$	0.43	3.00
					$SI_{YB} = 7.717 + 0.948\ (SI_{B})$		

continued

Table 2.—continued

Comp. no.	Species compared	Study†	No. of plots	SI range (ft.)	Models	Coeff. of determ. (R^2)	Std. error of estimate (%)
24a§					$SI_{YB} = 38.764 + 0.630\ (SI_B) - 3.060\ (dr)$	0.65	2.29
					$SI_B = -11.994 + 0.897\ (SI_{YB}) + 2.858\ (dr)$	0.57	2.74
					$SI_{YB} = 27.645 + 0.842\ (SI_B) - 2.959\ (dr)$		
25	Yellow birch	6	70	40-76	$SI_{YB} = 2.585 + 0.883\ (SI_{AB})$	0.78	3.45
	vs. Am. basswood		70	45-78	$SI_{AB} = 11.951 + 0.880\ (SI_{YB})$	0.78	3.44
					$SI_{YB} = -4.758 + 0.998\ (SI_{AB})$		
26	Yellow birch	6	60	43-76	$SI_{YB} = 11.861 + 0.746\ (SI_{AE})$	0.78	2.93
	vs. Am. elm		60	47-81	$SI_{AE} = 1.371 + 1.050\ (SI_{YB})$	0.78	3.47
					$SI_{YB} = 5.216 + 0.850\ (SI_{AE})$		
27	Yellow birch	6	37	43-76	$SI_{YB} = 12.318 + 0.715\ (SI_{WA})$	0.68	4.02
	vs. white ash		37	46-84	$SI_{WA} = 9.273 + 0.956\ (SI_{YB})$	0.68	4.65
					$SI_{YB} = 1.885 + 0.872\ (SI_{WA})$		
28	Yellow birch	6	20	48-68	$SI_{YB} = 22.082 + 0.585\ (SI_{BA})$	0.61	3.49
	vs. black ash		20	52-78	$SI_{BA} = 1.628 + 1.049\ (SI_{YB})$	0.61	4.68
					$SI_{YB} = 11.436 + 0.751\ (SI_{BA})$		
28a§					$SI_{YB} = 22.159 + 0.656\ (SI_{BA}) - 1.792\ (dr)$	0.80	2.84
					$SI_{BA} = -6.289 + 1.069\ (SI_{YB}) + 2.618\ (dr)$	0.81	2.30
					$SI_{YB} = 14.950 + 0.781\ (SI_{BA}) - 2.205\ (dr)$		
29	Yellow birch	6	14	51-68	$SI_{YB} = 3.045 + 0.849\ (SI_{NRO})$	0.74	2.52
	vs. n. red oak		14	58-72	$SI_{NRO} = 14.390 + 0.867\ (SI_{YB})$	0.74	2.55
					$SI_{YB} = -6.197 + 0.992\ (SI_{NRO})$		
30	Yellow birch	6	25	42-71	$SI_{YB} = 18.053 + 0.674\ (SI_{BC})$	0.61	4.06
	vs. black cherry		25	42-73	$SI_{BC} = 7.385 + 0.899\ (SI_{YB})$	0.61	4.69
					$SI_{YB} = 6.718 + 0.863\ (SI_{BC})$		
31	Yellow birch	6	16	42-67	$SI_{YB} = -0.735 + 0.903\ (SI_{WB})$	0.73	3.79
	vs. white birch		16	47-72	$SI_{WB} = 17.342 + 0.806\ (SI_{YS})$	0.73	3.58
					$SI_{YB} = -10.258 + 1.058\ (SI_{WB})$		
32	Yellow birch	6	7	53-76	$SI_{YB} = -5.865 + 0.934\ (SI_A)$	0.89	3.75
	vs. aspens		7	53-85	$SI_A = 12.670 + 0.958\ (SI_{YB})$	0.89	3.80
					$SI_{YB} = -9.885 + 0.994\ (SI_A)$		
33	Am. basswood	6	86	48-80	$SI_{AB} = 14.611 + 0.770\ (SI_{AE})$	0.70	3.59
	vs. Am. elm		86	47-81	$SI_{AE} = 6.421 + 0.904\ (SI_{AB})$	0.70	3.89
					$SI_{AB} = 4.856 + 0.921\ (SI_{AE})$		
34	Am. basswood	6	64	45-80	$SI_{AB} = 18.977 + 0.689\ (SI_{WA})$	0.70	3.66
	vs. white ash		64	44-84	$SI_{WA} = 0.885 + 1.012\ (SI_{AB})$	0.70	4.45
					$SI_{AB} = 9.642 + 0.828\ (SI_{WA})$		
35	Am. basswood	6	31	47-78	$SI_{AB} = 13.427 + 0.797\ (SI_{BA})$	0.63	4.19
	vs. black ash		31	51-78	$SI_{BA} = 13.243 + 0.789\ (SI_{AB})$	0.63	4.17
					$SI_{AB} = -0.256 + 1.101\ (SI_{BA})$		
36	Am. basswood	6	29	45-75	$SI_{AB} = -5.183 + 1.065\ (SI_{NRO})$	0.76	3.10
	vs. n. red oak		29	50-74	$SI_{NRO} = 19.132 + 0.711\ (SI_{AB})$	0.76	2.53
					$SI_{AB} = -15.079 + 1.221\ (SI_{NRO})$		

continued

Table 2.—continued

Comp. no.	Species compared	Study†	No. of plots	SI range (ft.)	Models	Coeff. of determ. (R^2)	Std. error of estimate (%)
36a§					SI_{AB} = -4.459 + 1.107 (SI_{NRO}) - 1.166 (dr)	0.80	2.84
					SI_{NRO} = 15.415 + 0.725 (SI_{AB}) + 0.980 (dr)	0.81	2.30
					SI_{AB} = -12.118 + 1.232 (SI_{NRO}) -1.703 (dr)		
37	Am. basswood	6	15	50-74	SI_{AB} = 26.527 + 0.592 (SI_{BC})	0.68	3.96
	vs. black cherry		15	49-74	SI_{BC} = -10.699 + 1.151 (SI_{AB})	0.68	5.53
					SI_{AB} = 18.257 + 0.725 (SI_{BC})		
38	Am. basswood	6	20	49-74	SI_{AB} = 9.115 + 0.825 (SI_{WB})	0.67	3.81
	vs. white birch		20	47-72	SI_{WB} = 13.238 + 0.813 (SI_{AB})	0.67	3.78
					SI_{AB} = -1.913 + 1.001 (SI_{WB})		
39	Am. basswood	6	8	45-78	SI_{AB} = 1.482 + 0.855 (SI_A)	0.72	6.40
	vs. aspens		8	53-85	SI_A = 17.712 + 0.847 (SI_{AB})	0.72	6.37
					SI_{AB} = -8.775 + 1.004 (SI_A)		
40	Trembling aspen	2	16	40-80	SI_{TA} = 22.41 + 0.75 (SI_{AB})	0.45	8.1
	vs. Am. basswood		16	37-80	SI_{AB} = 20.49 + 0.59 (SI_{TA})	0.45	7.2
					SI_{TA} = 0.60 + 1.11 (SI_{AB})		
41	Am. elm	6	51	49-81	SI_{AE} = 10.769 + 0.807 (SI_{WA})	0.78	3.28
	vs. white ash		51	46-84	SI_{WA} = 4.696 + 0.963 (SI_{AE})	0.78	3.58
					SI_{AE} = 3.405 + 0.916 (SI_{WA})		
41a§					SI_{AE} = 10.869 + 0.833 (SI_{WA}) - 0.704 (dr)	0.79	3.22
					SI_{WA} = 3.201 + 0.946 (SI_{AE}) + 1.003 (dr)	0.79	3.43
					SI_{AE} = 4.066 + 0.940 (SI_{WA}) - 0.854 (dr)		
42	Am. elm	6	34	45-76	SI_{AE} = 13.004 + 0.804 (SI_{BA})	0.65	4.19
	vs. black ash		34	48-76	SI_{BA} = 11.452 + 0.814 (SI_{AE})	0.65	4.22
					SI_{AE} = 0.946 + 0.993 (SI_{BA})		
42a§					SI_{AE} = 3.775 + 0.888 (SI_{BA}) + 6 .190 (dr) - 1.671 (dr2)	0.78	3.46
					SI_{BA} = 10.381 + 0.852 (SI_{AE}) - 4.166 (dr) + 1.321 (dr2)	0.79	3.39
					SI_{AE} = -2.945 + 1.010 (SI_{BA}) + 5.178 (dr) - 1.496 (dr2)		
43	Am. elm	6	15	60-75	SI_{AE} = 7.671 + 0.903 (SI_{NRO})	0.39	3.91
	vs. n. red oak		15	59-72	SI_{NRO} = 35.862 + 0.429 (SI_{AE})	0.39	2.69
					SI_{AE} = -24.195 + 1.402 (SI_{NRO})		
44	Am. elm	6	16	47-73	SI_{AE} = 14.628 + 0.792 (SI_{BC})	0.78	3.89
	vs. black cherry		16	42-74	SI_{BC} = -0.755 + 0.984 (SI_{AE})	0.78	4.33
					SI_{AE} = 8.384 + 0.893 (SI_{BC})		
45	Am. elm	6	12	49-76	SI_{AE} = 5.168 + 0.899 (SI_{WB})	0.71	4.49
	vs. white birch		12	47-72	SI_{WB} = 14.042 + 0.784 (SI_{AE})	0.71	4.20
					SI_{AE} = -5.084 + 1.066 (SI_{WB})		
46	Am. elm	6	7	49-81	SI_{AE} = 5.206 + 0.816 (SI_A)	0.83	4.81
	vs. aspens		7	53-85	SI_A = 6.593 + 1.011 (SI_{AE})	0.83	5.35
					SI_{AE} = -0.214 + 0.896 (SI_A)		

continued

Table 2.—continued

Comp. no.	Species compared	Study†	No. of plots	SI range (ft.)	Models	Coeff. of determ. (R^2)	Std. error of estimate (%)
47	White ash	6	27	51-76	$SI_{WA} = 3.969 + 0.981\ (SI_{BA})$	0.75	3.44
	vs. black ash		27	52-76	$SI_{BA} = 12.862 + 0.766\ (SI_{WA})$	0.75	3.04
					$SI_{WA} = -5.428 + 1.128\ (SI_{BA})$		
48	White ash	6	22	44-76	$SI_{WA} = -22.933 + 1.362\ (SI_{NRO})$	0.77	3.95
	vs. n. red oak		22	50-72	$SI_{NRO} = 27.478 + 0.566\ (SI_{WA})$	0.77	2.55
					$SI_{WA} = -34.762 + 1.549\ (SI_{NRO})$		
48a§					$SI_{WA} = -22.374 + 1.414\ (SI_{NRO}) -1.419\ (dr)$	0.81	3.70
					$SI_{NRO} = 24.477 + 0.573\ (SI_{WA}) + 0.956\ (dr)$	0.82	2.35
					$SI_{WA}= -31.350 + 1.561\ (SI_{NRO}) - 1.188\ (dr)$		
49	White ash	6	9	46-74	$SI_{WA} = -3.853 + 1.023\ (SI_{WB})$	0.69	5.18
	vs. white birch		9	47-70	$SI_{WB} = 21.765 + 0.674\ (SI_{WA})$	0.69	4.21
					$SI_{WA} = -16.344 + 1.225\ (SI_{WB})$		
50	White ash	6	7	44-84	$SI_{WA} = -17.000 + 1.111\ (SI_{A})$	0.85	5.86
	vs. aspens		7	60-85	$SI_{A} = 23.089 + 0.767\ (SI_{WA})$	0.85	4.87
					$SI_{WA} = -23.105 + 1.201\ (SI_{A})$		
51	Black ash	6	10	52-76	$SI_{BA} = -9.946 + 1.154\ (SI_{NRO})$	0.51	4.99
	vs. n. red oak		10	58-72	$SI_{NRO} = 35.708 + 0.444\ (SI_{BA})$	0.51	3.09
					$SI_{BA} = -37.214 + 1.579\ (SI_{NRO})$		
52	Black ash	1	8	42-72	$SI_{BA} = 23.68 + 0.57\ (SI_{BP})$	0.49	6.8
	vs. balsam poplar		8	35-78	$SI_{BP} = 3.23 + 0.99\ (SI_{BA})$	0.49	9.0
					$SI_{BA} = 11.71 + 0.77\ (SI_{BP})$		
53	N. red oak	1	37	33-83	$SI_{NRO} = 7.99 + 0.95\ (SI_{WO})$	0.77	6.6
	vs. white oak		37	25-79	$SI_{WO} = 5.48 + 0.82\ (SI_{NRO})$	0.77	6.2
					$SI_{WO} = -1.24 + 0.94\ (SI_{NRO})$		
54	N. red oak	1	106	36-100	$SI_{NRO} = 6.74 + 0.82\ (SI_{TA})$	0.48	8.4
	vs. trembling aspen		106	42-94	$SI_{TA} = 29.63 + 0.59\ (SI_{NRO})$	0.48	7.1
					$SI_{TA} = 13.86 + 0.86\ (SI_{NRO})$		
55	N. red oak	1	58	37-94	$SI_{NRO} = 9.93 + 0.77\ (SI_{BA})$	0.55	7.2
	vs. bigtooth aspen		58	46-91	$SI_{BA} = 24.23 + 0.73\ (SI_{NRO})$	0.55	5.7
					$SI_{BA} = 7.99 + 0.98\ (SI_{NRO})$		
56	N. red oak	6	7	50-74	$SI_{NRO} = 15.208 + 0.672\ (SI_{A})$	0.59	5.38
	vs. aspens		7	56-80	$SI_{A} = 13.919 + 0.883\ (SI_{NRO})$	0.59	6.16
					$SI_{NRO} = 1.756 + 0.872\ (SI_{A})$		
57	N. red oak	6	15	50-74	$SI_{NRO} = 0.014 + 0.997\ (SI_{WB})$	0.63	4.35
	vs. white birch		15	54-70	$SI_{WB} = 23.734 + 0.628\ (SI_{NRO})$	0.63	3.46
					$SI_{NRO} = -16.401 + 1.255\ (SI_{WB})$		
58	Trembling aspen	2	106	43-90	$SI_{TA} = 24.36 + 0.67\ (SI_{WB})$	0.51	6.2
	vs. white birch		106	37-82	$SI_{WB} = 9.87 + 0.75\ (SI_{TA})$	0.51	6.6
					$SI_{TA} = 8.50 + 0.95\ (SI_{WB})$		
59	White birch	1	25	46-76	$SI_{WB} = 24.28 + 0.56\ (SI_{BA})$	0.61	5.0
	vs. bigtooth aspen		25	46-91	$SI_{BA} = -1.48 + 1.11\ (SI_{WB})$	0.61	7.0
					$SI_{WB} = 13.93 + 0.71\ (SI_{BA})$		

continued

Table 2.—continued

Comp. no.	Species compared	Study†	No. of plots	SI range (ft.)	Models	Coeff. of determ. (R^2)	Std. error of estimate (%)
60	White birch	6	7	47-69	$SI_{WB} = 5.271 + 0.849 (SI_A)$	0.91	2.37
	vs. aspens		7	53-75	$SI_A = -0.239 + 1.077 (SI_{WB})$	0.91	2.67
					$SI_{WB} = 2.296 + 0.818 (SI_A)$		
61	Trembling aspen	6	25	54-96	$SI_{TA} = 3.81 + 0.93 (SI_{BA})$	0.83	4.3
	vs. bigtooth aspen		25	54-94	$SI_{BA} = 7.99 + 0.90 (SI_{TA})$	0.83	4.2
					$SI_{BA} = 2.22 + 0.98 (SI_{TA})$		
62	Trembling aspen	6	122	30-96	$SI_{TA} = 19.53 + 0.75 (SI_{BP})$	0.51	8.0
	vs. balsam poplar		122	30-86	$SI_{BP} = 14.53 + 0.69 (SI_{TA})$	0.51	7.6
					$SI_{BP} = -2.68 + 0.96 (SI_{TA})$		
63	Black cherry	5	11	68-93	$SI_{BC} = 49.45 + 0.42 (SI_{BH})$	0.68	6.6
	vs. bitternut hickory			62-104	$SI_{BH} = -55.49 + 1.63 (SI_{BC})$	0.68	13.0
					$SI_{BH} = -88.69 + 2.00 (SI_{BC})$		
64◊	Jack pine	1	48	43-80	$SI_{JP} = 12.09 + 0.82 (SI_{RP})$	0.63	5.3
	vs. red pine		48	43-79	$SI_{RP} = 11.97 + 0.77 (SI_{JP})$	0.63	5.2
					$SI_{JP} = -0.08 + 1.03 (SI_{RP})$		
65‡	Jack pine	4	39	30-74	$SI_{JP} = 0.46 + 1.01 (SI_{BS})$	0.80	5.1
	black spruce		39	28-69	$SI_{BS} = 9.45 + 0.79 (SI_{JP})$	0.80	4.5
					$SI_{JP} = -5.71 + 1.13 (SI_{BS})$		
66‡	Jack pine	3	6	46-59	$SI_{JP} = -4.89 + 1.00 (SI_T)$	0.60	2.4
	vs. tamarack		6	51-62	$SI_T = -5.75 + 0.60 (SI_{JP})$	0.60	2.0
					$SI_{JP} = -21.26 + 1.29 (SI_T)$		
67‡	Jack pine	4	26	28-72	$SI_{JP} = 15.94 + 0.67 (SI_{TA})$	0.69	5.9
	vs. trembling aspen		26	30-74	$SI_{TA} = -0.10 + 1.04 (SI_{JP})$	0.69	7.3
					$SI_{JP} = 8.01 + 0.81 (SI_{TA})$		
68	Jack pine	1	7	52-83	$SI_{JP} = 1.53 + 1.09 (SI_{WB})$	0.62	6.3
	vs. white birch		7	49-68	$SI_{WB} = 18.12 + 0.63 (SI_{JP})$	0.62	4.8
					$SI_{JP} = -11.77 + 1.31 (SI_{WB})$		
69◊	Red pine	1	77	37-75	$SI_{RP} = 12.12 + 0.80 (SI_{WP})$	0.70	4.7
	vs. white pine		77	29-71	$SI_{WP} = 5.04 + 0.88 (SI_{RP})$	0.70	4.9
					$SI_{RP} = 3.93 + 0.96 (SI_{WP})$		
70	Red pine	1	15	43-70	$SI_{RP} = 26.58 + 0.56 (SI_{WS})$	0.65	4.0
	vs. white spruce		15	36-67	$SI_{WS} = -11.87 + 1.17 (SI_{RP})$	0.65	5.8
					$SI_{RP} = 18.90 + 0.70 (SI_{WS})$		
71	Red pine	1	8	51-75	$SI_{RP} = 23.60 + 0.59 (SI_{RM})$	0.61	5.3
	vs. red maple		8	38-75	$SI_{RM} = -2.03 + 1.04 (SI_{RP})$	0.61	7.0
					$SI_{RP} = 13.60 + 0.76 (SI_{RM})$		
72	White pine	5	23	58-98	$SI_{WP} = 16.52 + 0.85 (SI_{WS})$	0.71	10.7
	vs. white spruce		23	53-93	$SI_{WS} = 8.75 + 0.84 (SI_{WP})$	0.71	10.0
					$SI_{WS} = -5.50 + 1.01 (SI_{WP})$		
73	White pine	1	14	41-72	$SI_{WP} = 0.15 + 0.94 (SI_{TA})$	0.72	5.7
	vs. trembling aspen		14	40-75	$SI_{TA} = 15.80 + 0.79 (SI_{WP})$	0.72	5.3
					$SI_{WP} = -9.00 + 1.09 (SI_{TA})$		

continued

Table 2.—continued

Comp. no.	Species compared	Study†	No. of plots	SI range (ft.)	Models	Coeff. of determ. (R^2)	Std. error of estimate (%)
74	White pine	1	10	46-87	$SI_{WP} = 21.50 + 0.68\ (SI_{RM})$	0.46	7.6
	vs. red maple		10	40-77	$SI_{RM} = 12.92 + 0.77\ (SI_{WP})$	0.46	8.2
					$SI_{WP} = 5.26 + 0.94\ (SI_{RM})$		
75‡	Black spruce	3	9	9-53	$SI_{BS} = -2.36 + 0.85\ (SI_T)$	0.91	4.3
	vs. tamarack		9	17-62	$SI_T = 7.02 + 1.06\ (SI_{BS})$	0.91	4.8
					$SI_{BS} = -4.33 + 0.89\ (SI_T)$		
76‡	Black spruce	4	19	31-66	$SI_{BS} = -5.74 + 1.00\ (SI_{TA})$	0.74	5.4
	vs. trembling aspen		19	45-71	$SI_{TA} = 19.35 + 0.74\ (SI_{BS})$	0.74	4.7
					$SI_{BS} = -15.94 + 1.17\ (SI_{TA})$		
77	White spruce	1	9	25-56	$SI_{WS} = -15.25 + 1.66\ (SI_{NWC})$	0.84	4.0
	vs. n. white cedar		9	24-40	$SI_{NWC} = 12.57 + 0.52\ (SI_{WS})$	0.84	2.2
					$SI_{WS} = -19.49 + 1.79\ (SI_{NWC})$		
78	White spruce	1	28	29-82	$SI_{WS} = 13.30 + 0.67\ (SI_{TA})$	0.42	9.7
	vs. trembling aspen		28	25-86	$SI_{TA} = 26.63 + 0.67\ (SI_{WS})$	0.42	9.7
					$SI_{WS} = -7.89 + 1.00\ (SI_{TA})$		
79	White spruce	5	23	31-86	$SI_{WS} = 2.62 + 0.90\ (SI_{NS})$	0.76	11.5
	vs. Norway spruce		23	48-97	$SI_{NS} = 16.66 + 0.88\ (SI_{WS})$	0.76	4.8
					$SI_{NS} = 7.40 + 0.97\ (SI_{WS})$		
80	Balsam fir	1	15	28-61	$SI_{BF} = -6.81 + 1.59\ (SI_{NWC})$	0.71	4.8
	vs. n. white cedar		15	25-40	$SI_{NWC} = 11.63 + 0.46\ (SI_{BF})$	0.71	2.6
					$SI_{BF} = -15.20 + 1.85\ (SI_{NWC})$		
81	Balsam fir	1	15	28-66	$SI_{BF} = 18.22 + 0.59\ (SI_{WB})$	0.68	6.0
	vs. white birch		15	26-77	$SI_{WB} = -6.62 + 1.20\ (SI_{BF})$	0.68	8.5
					$SI_{BF} = 12.10 + 0.71\ (SI_{WB})$		
82	Tamarack	1	10	25-55	$SI_T = -4.22 + 1.67\ (SI_{NWC})$	0.67	5.9
	vs. n. white cedar			21-35	$SI_{NWC} = 9.95 + 0.42\ (SI_T)$	0.67	3.0
					$SI_T = -12.71 + 1.98\ (SI_{NWC})$		

† Study: (1) Carmean and Hahn (1981) (4) Ortiz (1985)
(2) Carmean and Vasilevsky (1971) (5) Dillabough (1983)
(3) Thurston (1984) (6) Carmean (1979)

§ Drainage (dr) classes are: 1 = poorly drained; 2 = somewhat poorly drained; 3 = moderately well drained; 4 = well drained; and 5 = somewhat excessively drained (USCS 1975)

◊ Data for comparisons 64 and 69 were from USCS plots in Minnesota, Wisconsin and Michigan.

‡ Equations 65, 66, 67, 75 and 76 were metric equations in the original reports. Converting these equations to English equations involved multiplying the b_o coefficients by the 3.28 converting factor.

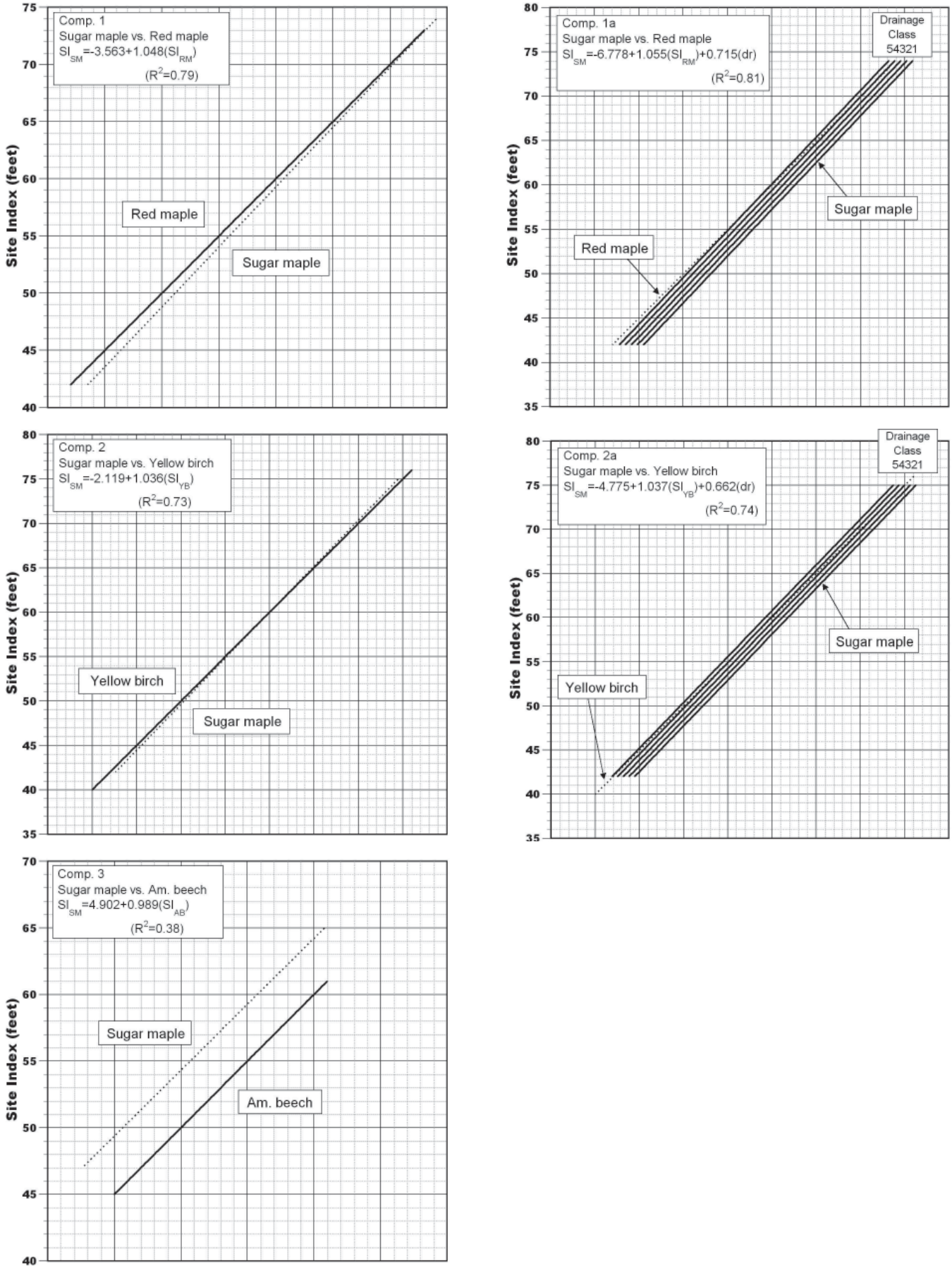
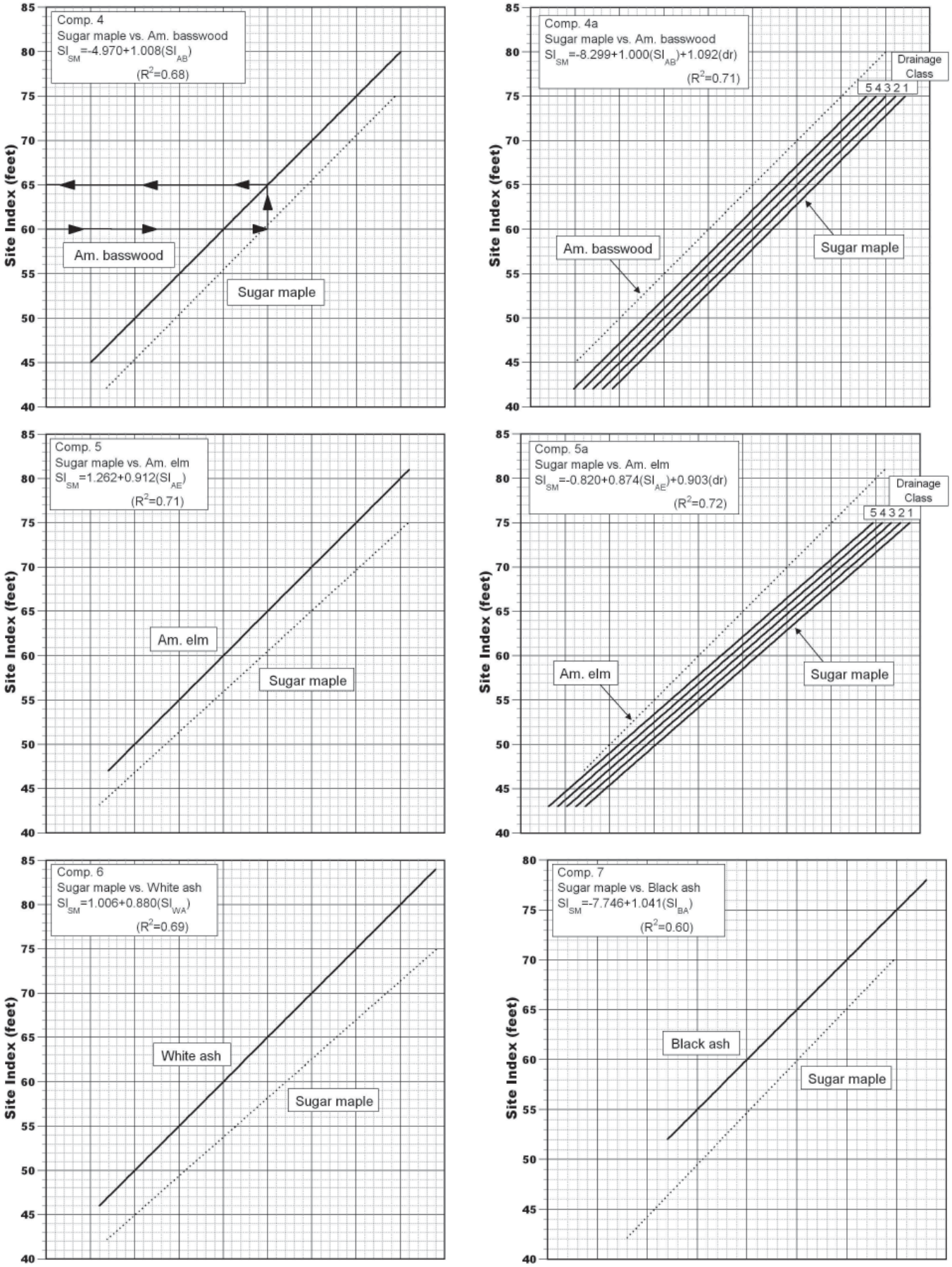


Figure 1.—Site index comparison graphs for 82 recommended models that express site index relations between hardwood and conifer species in the Upper Great Lakes area. These graphs were constructed using the average models listed in Table 2.



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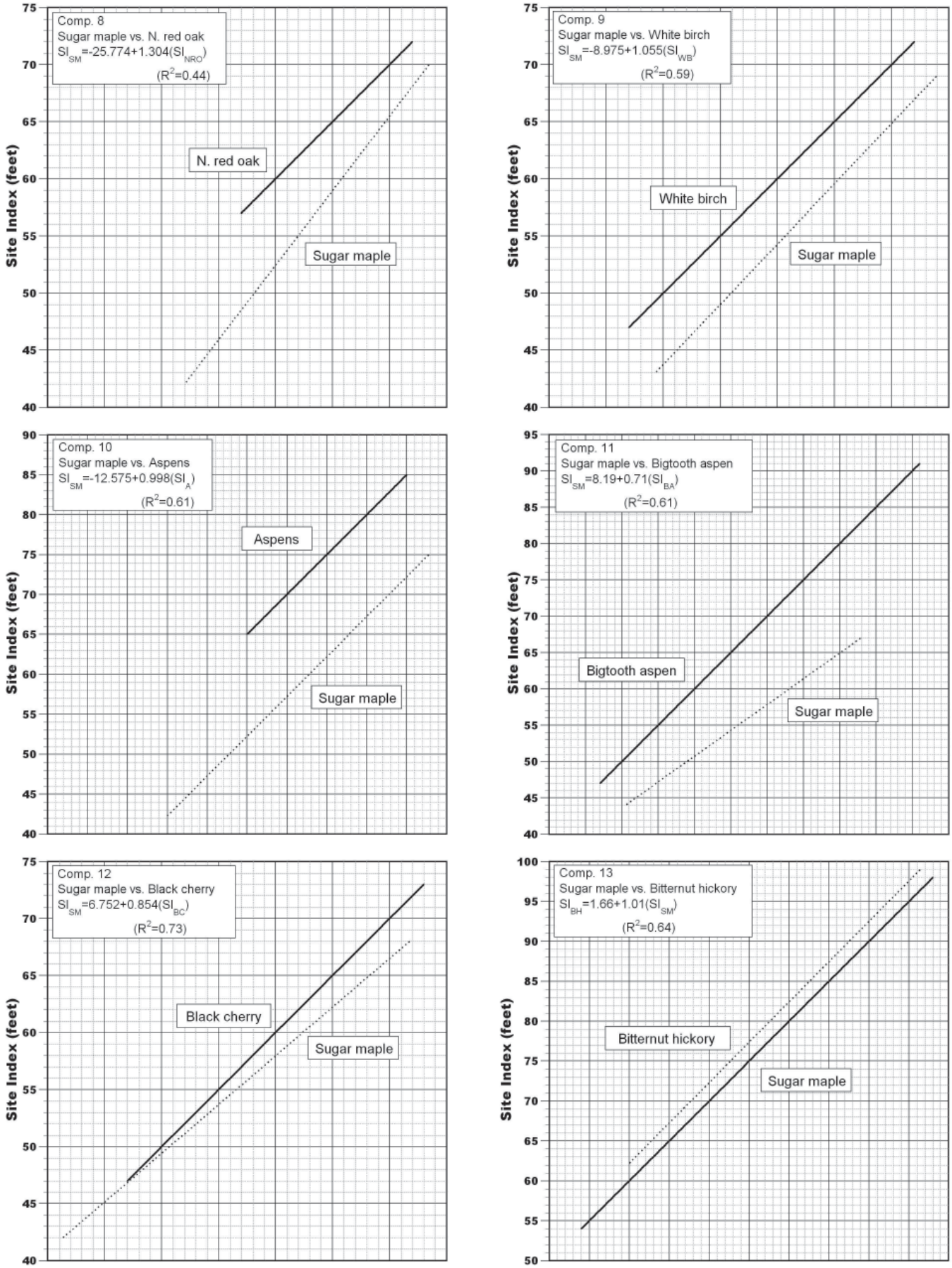

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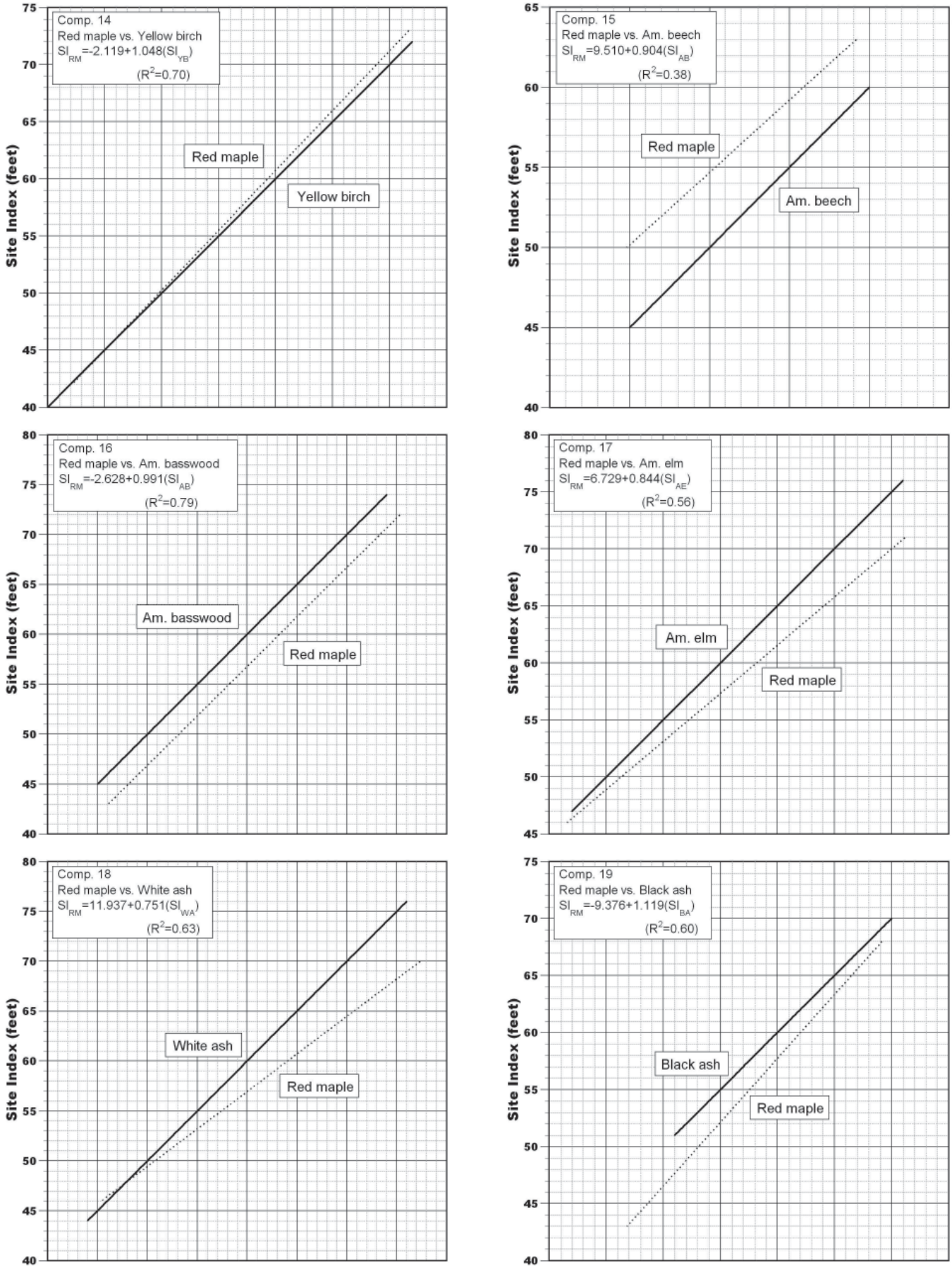

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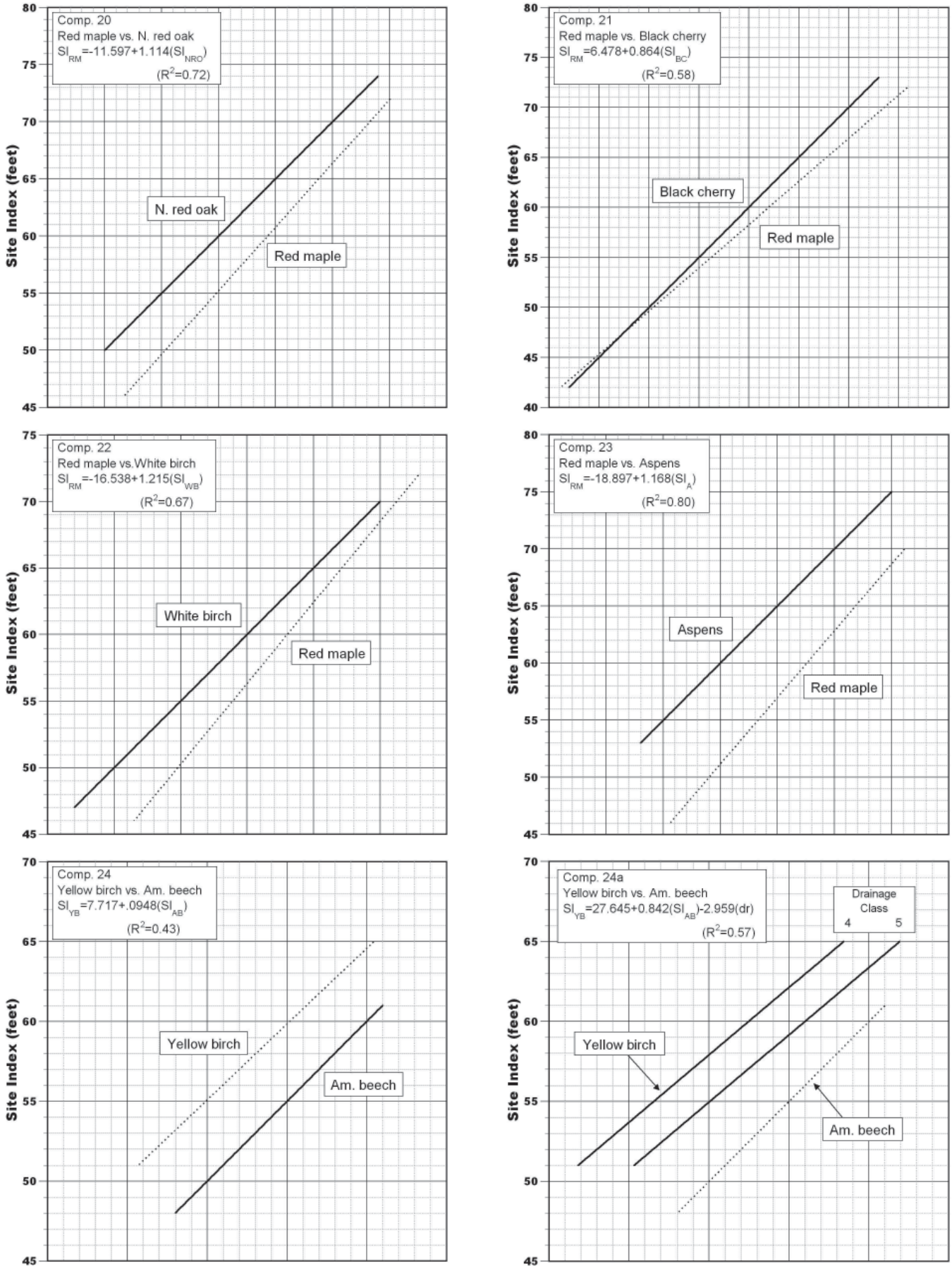

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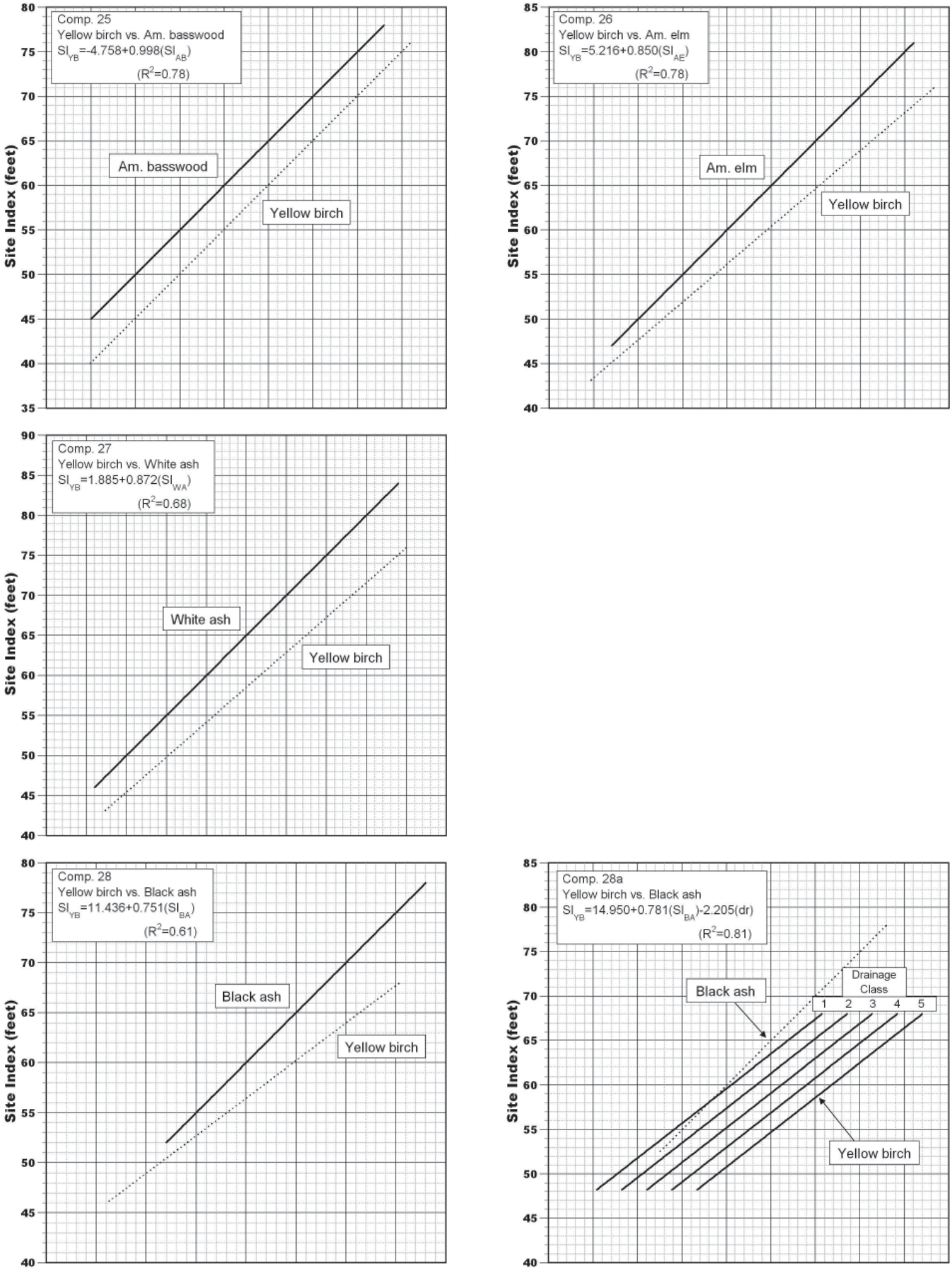

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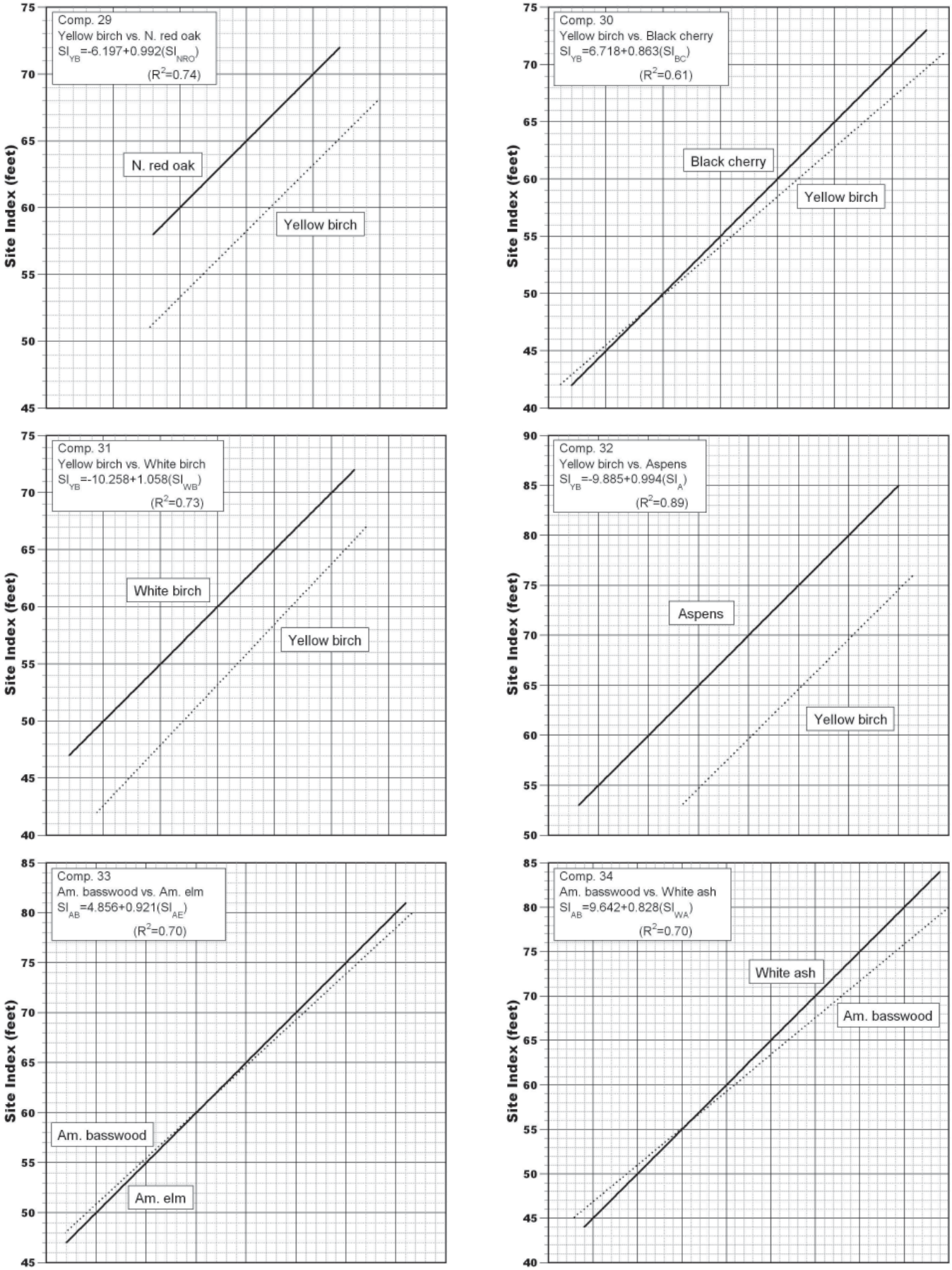

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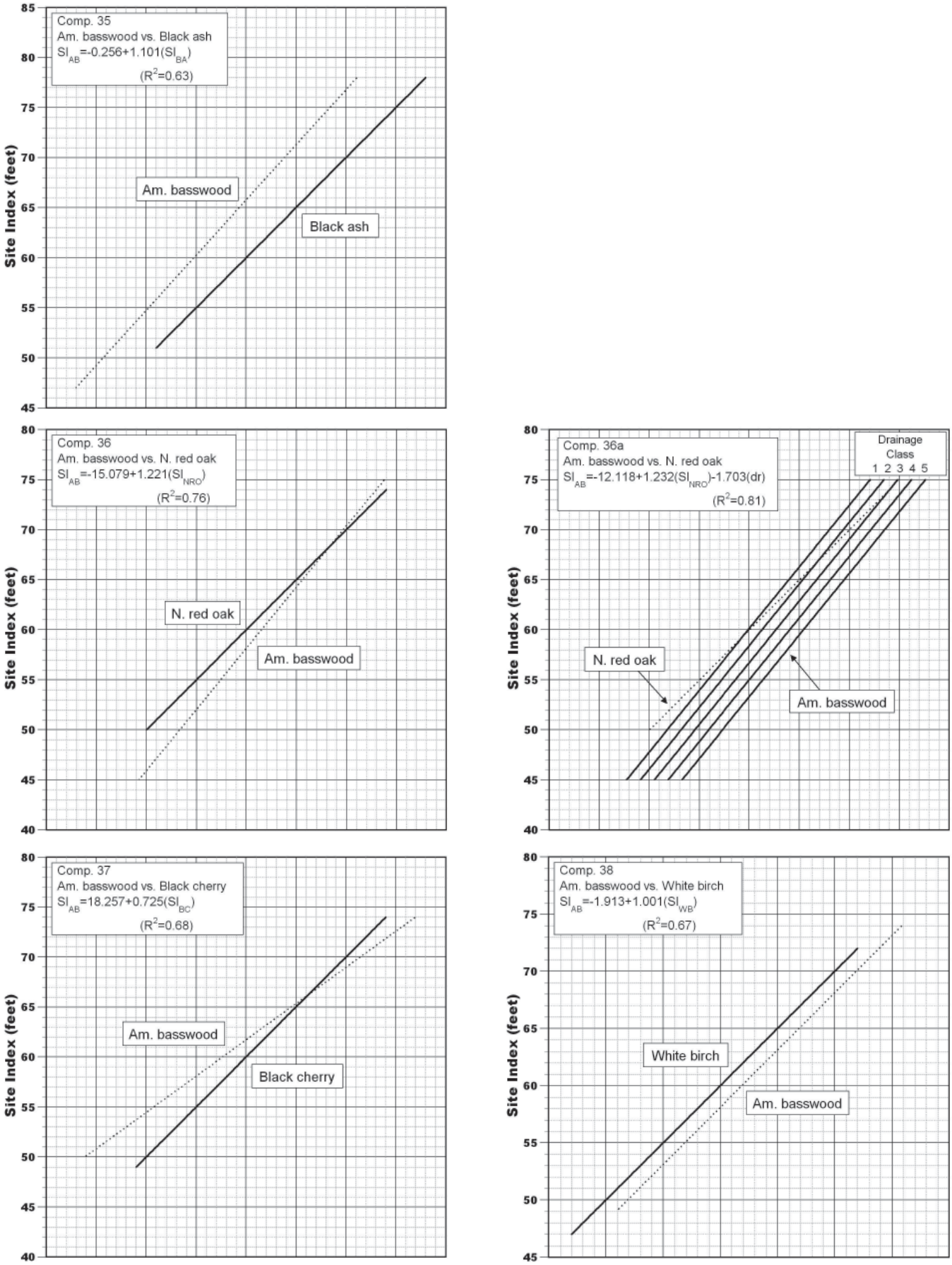

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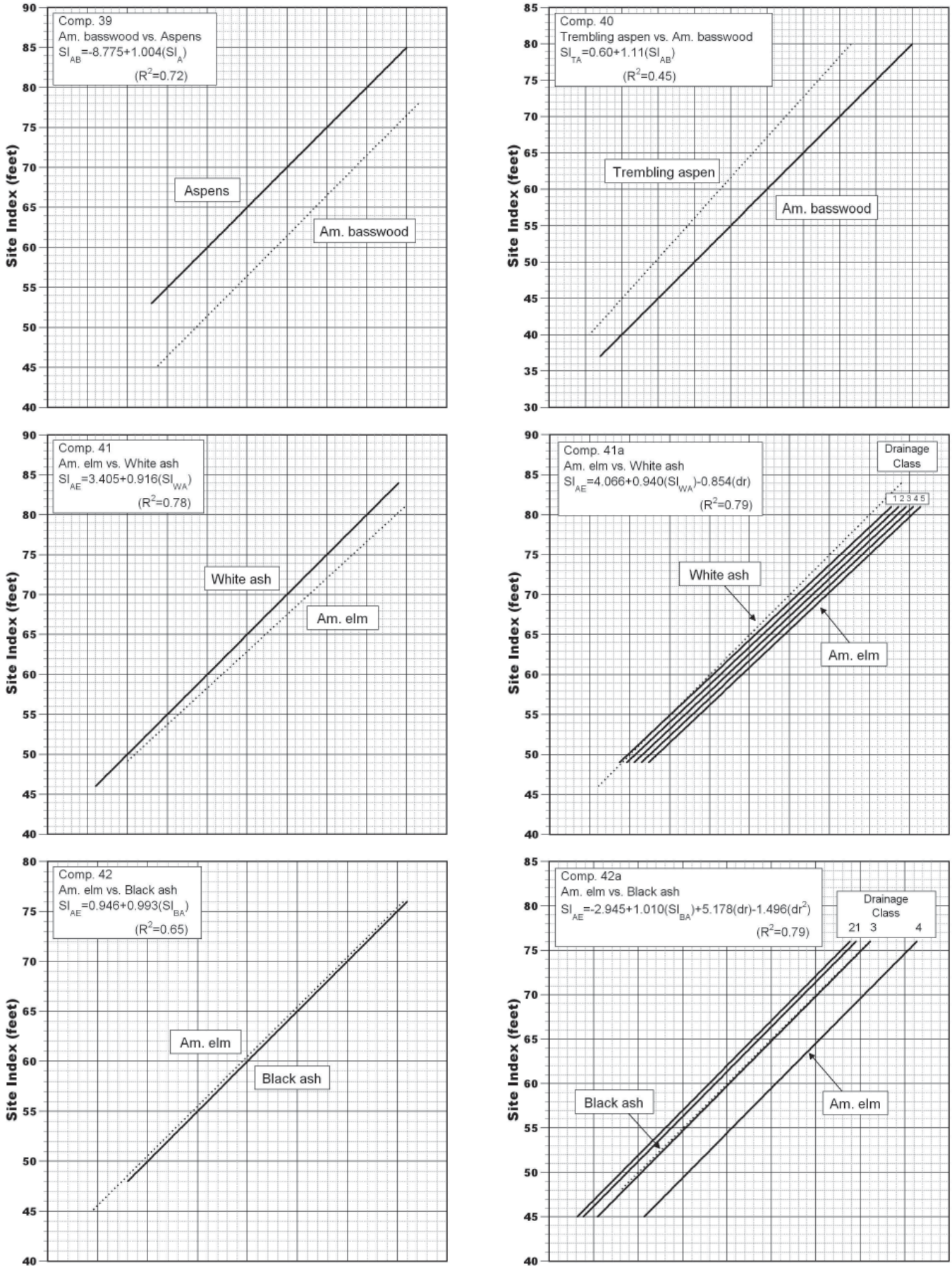

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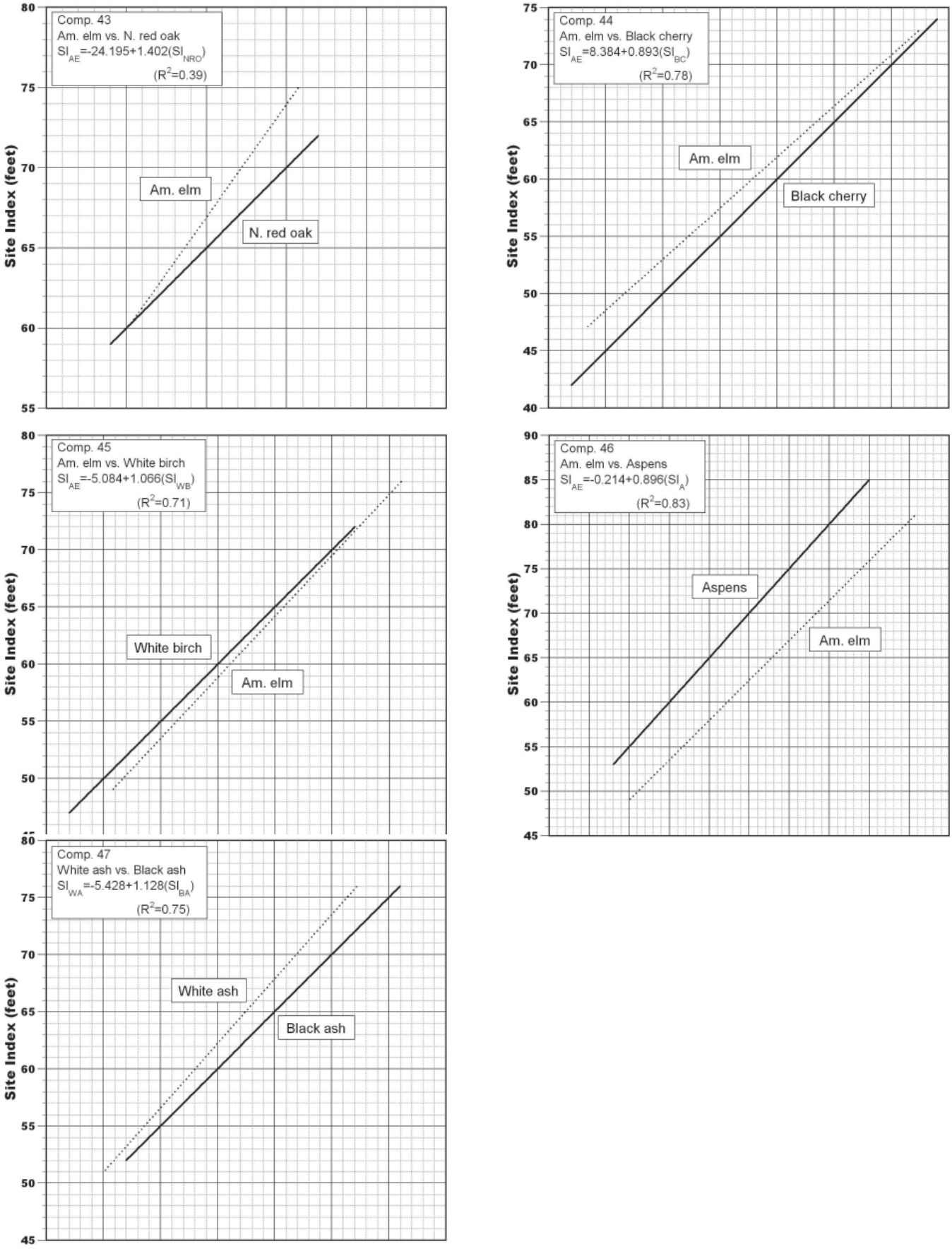

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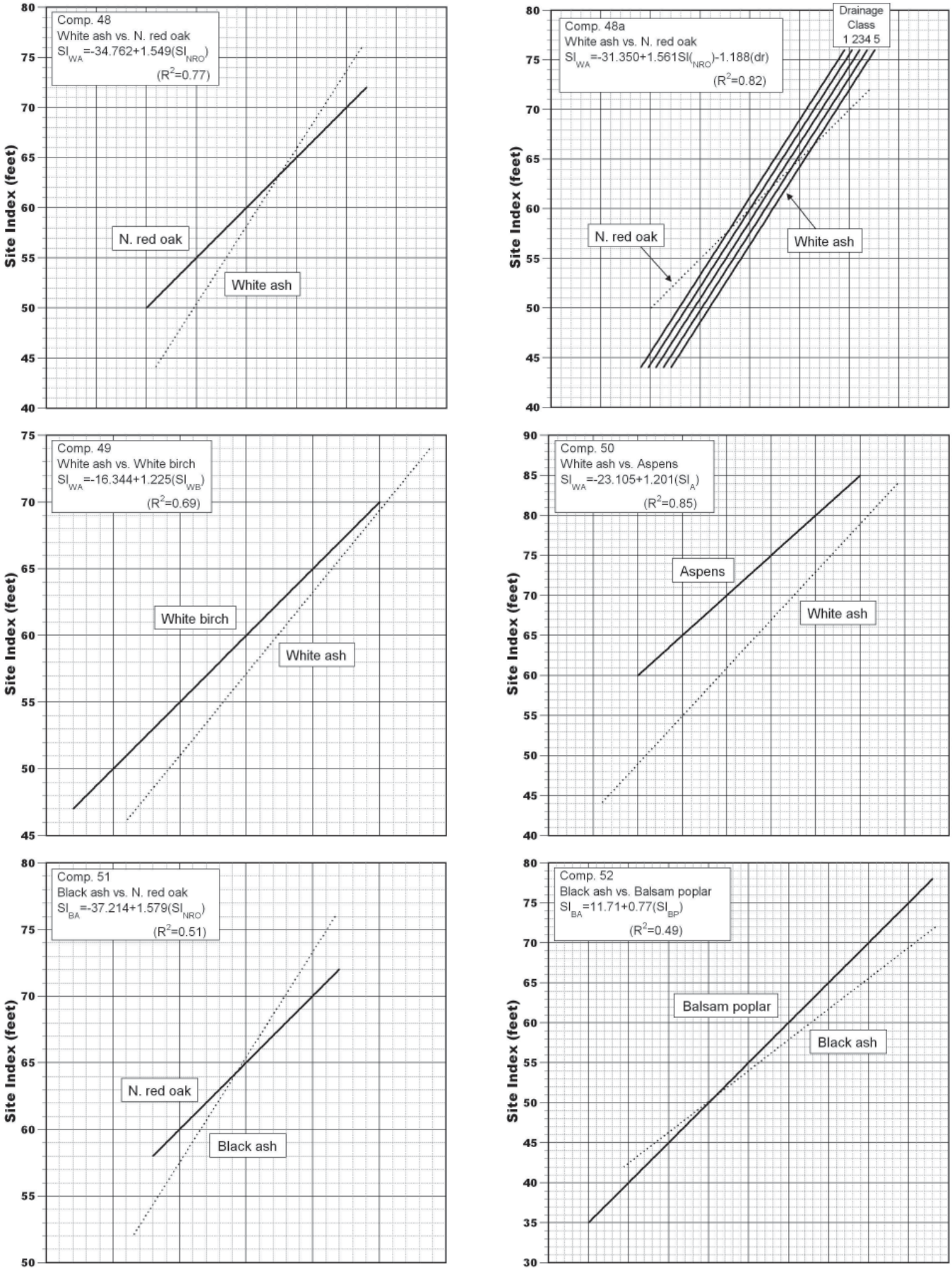

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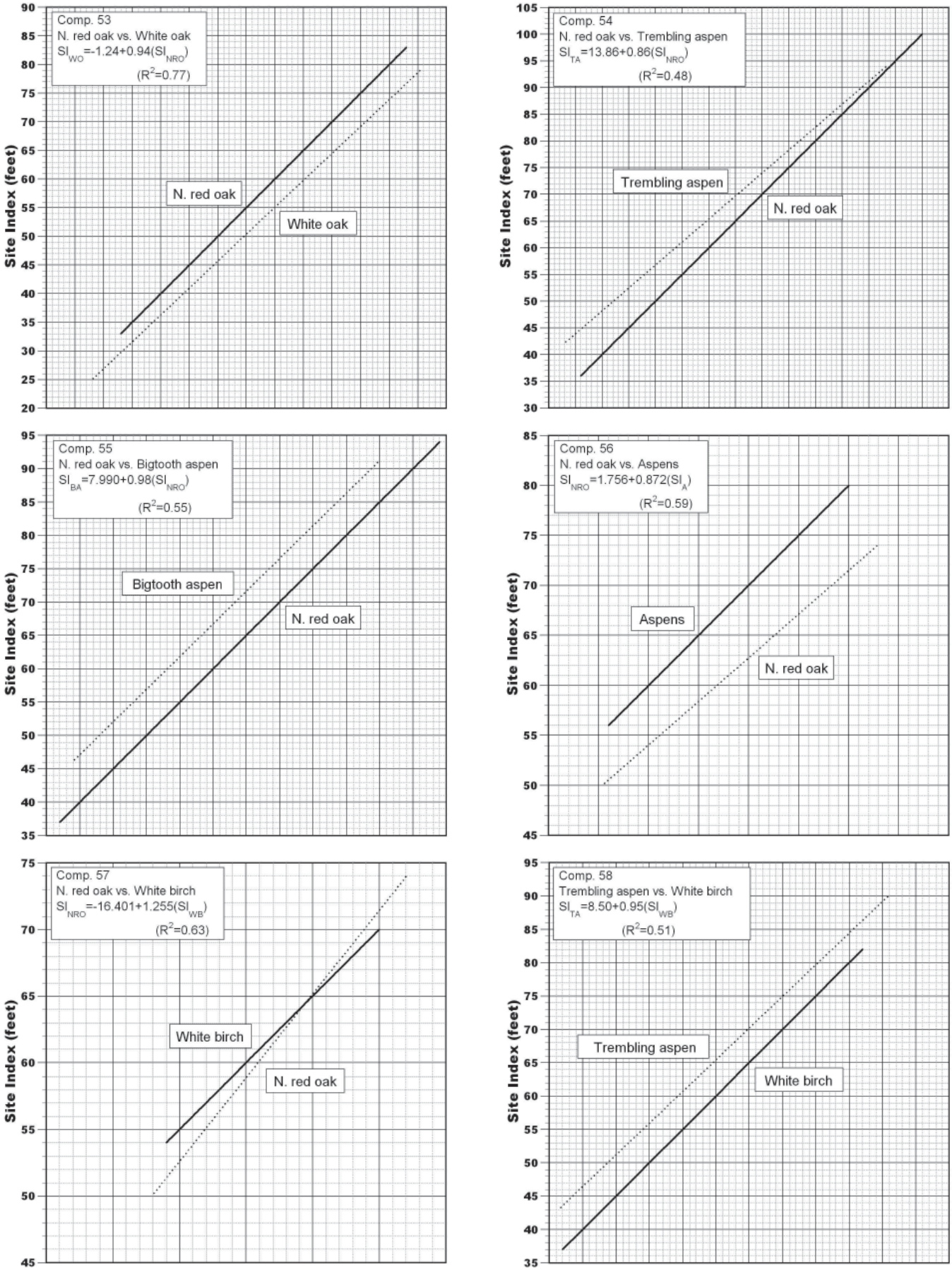

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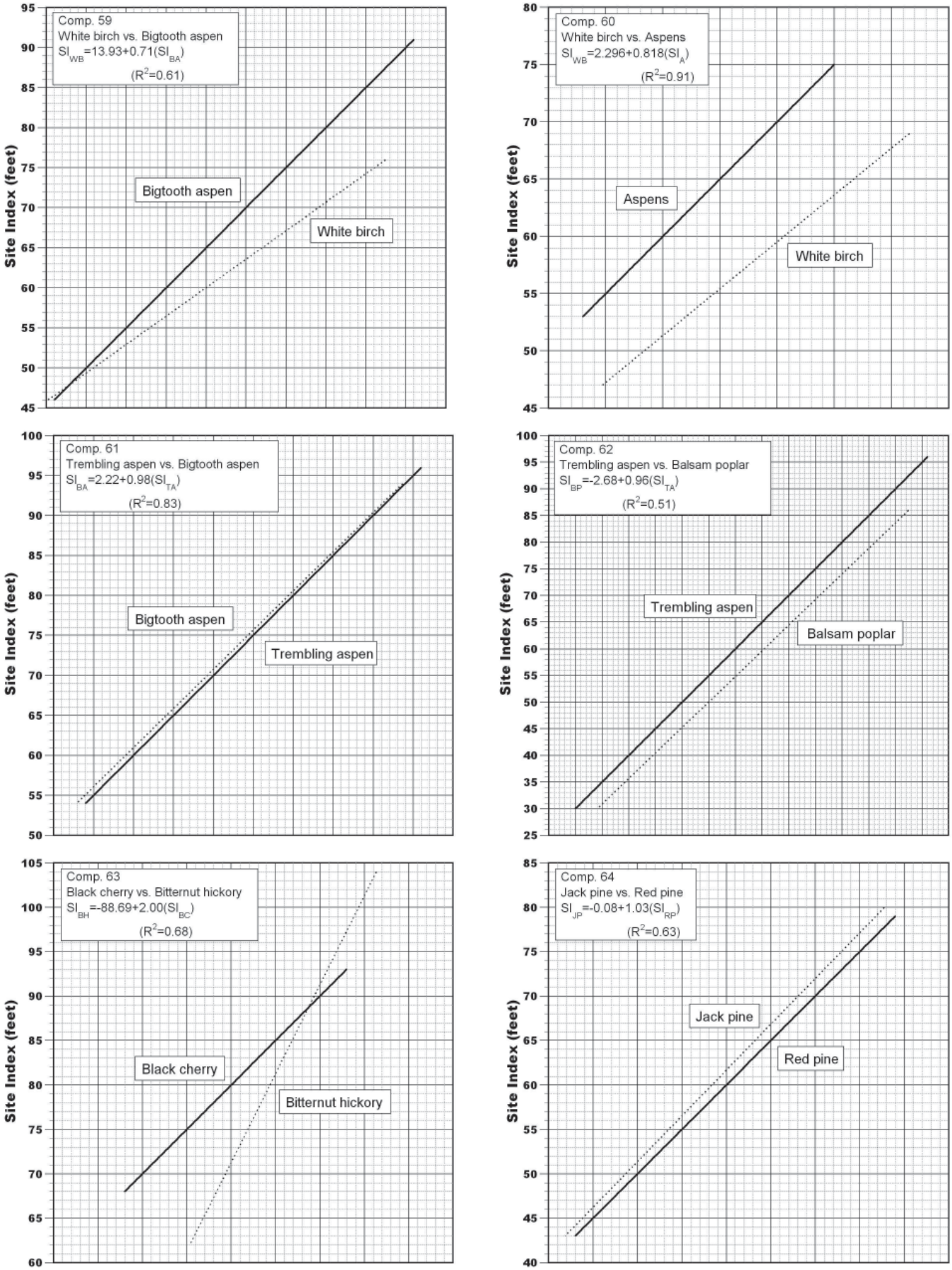

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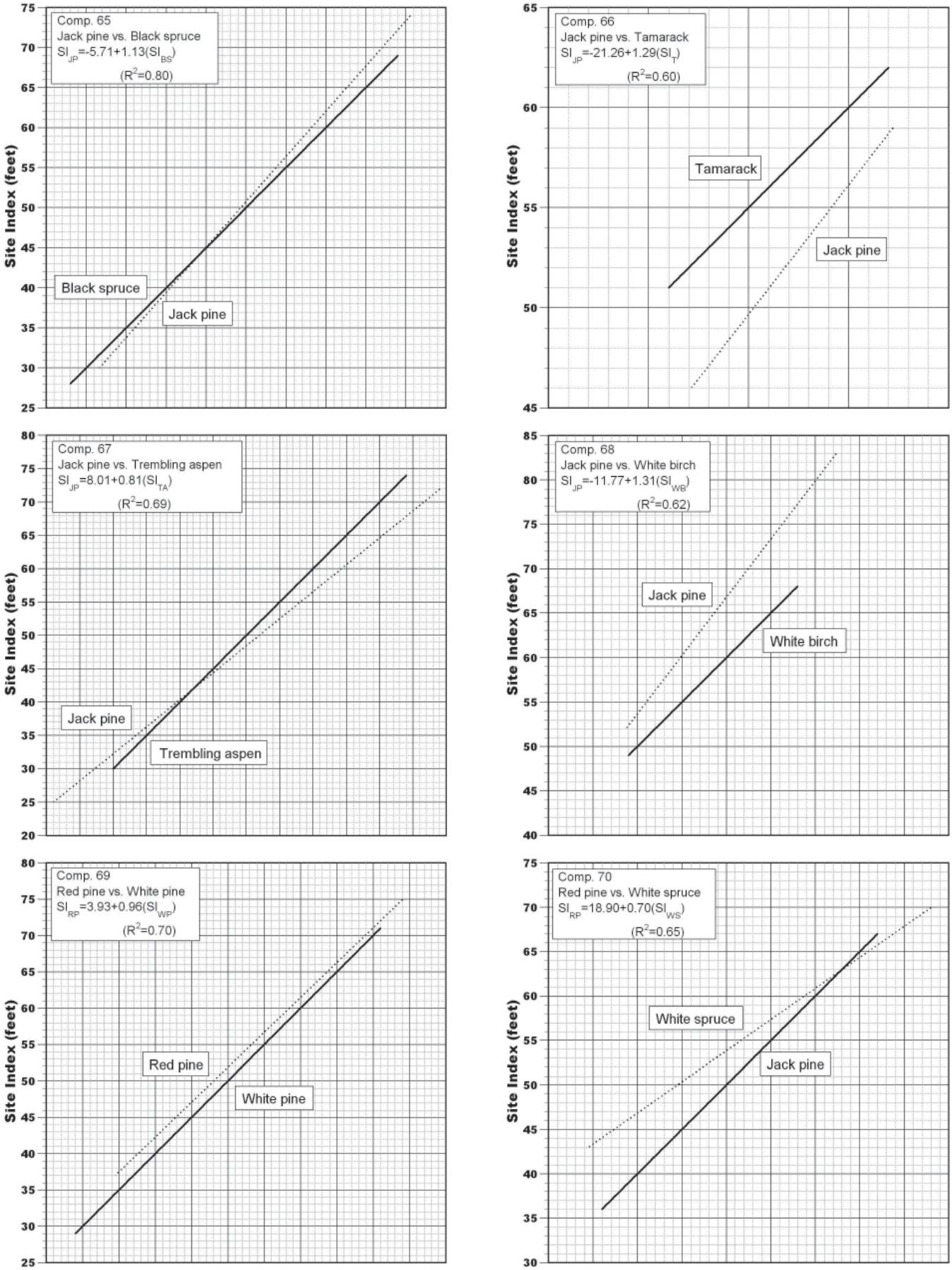

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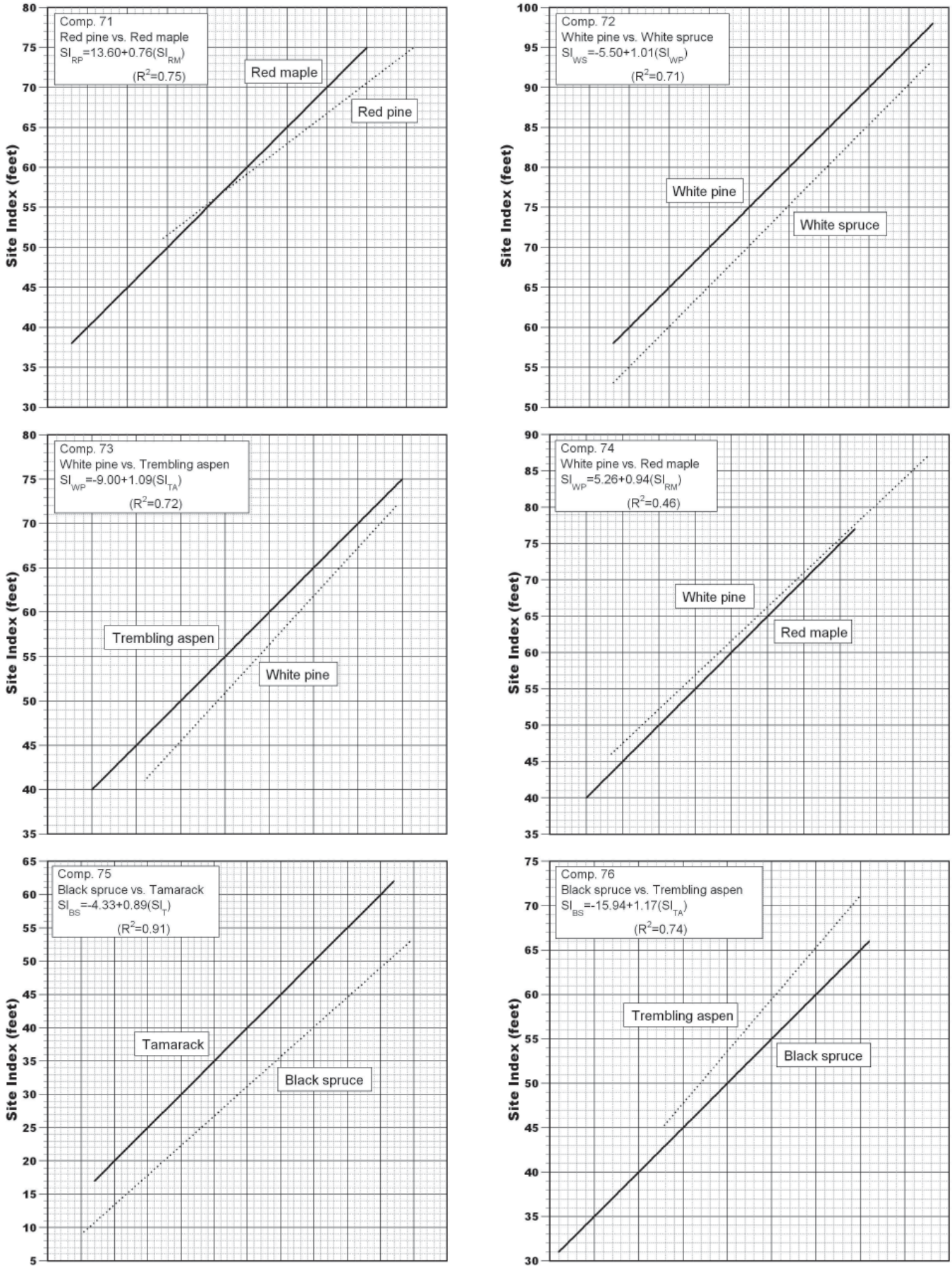

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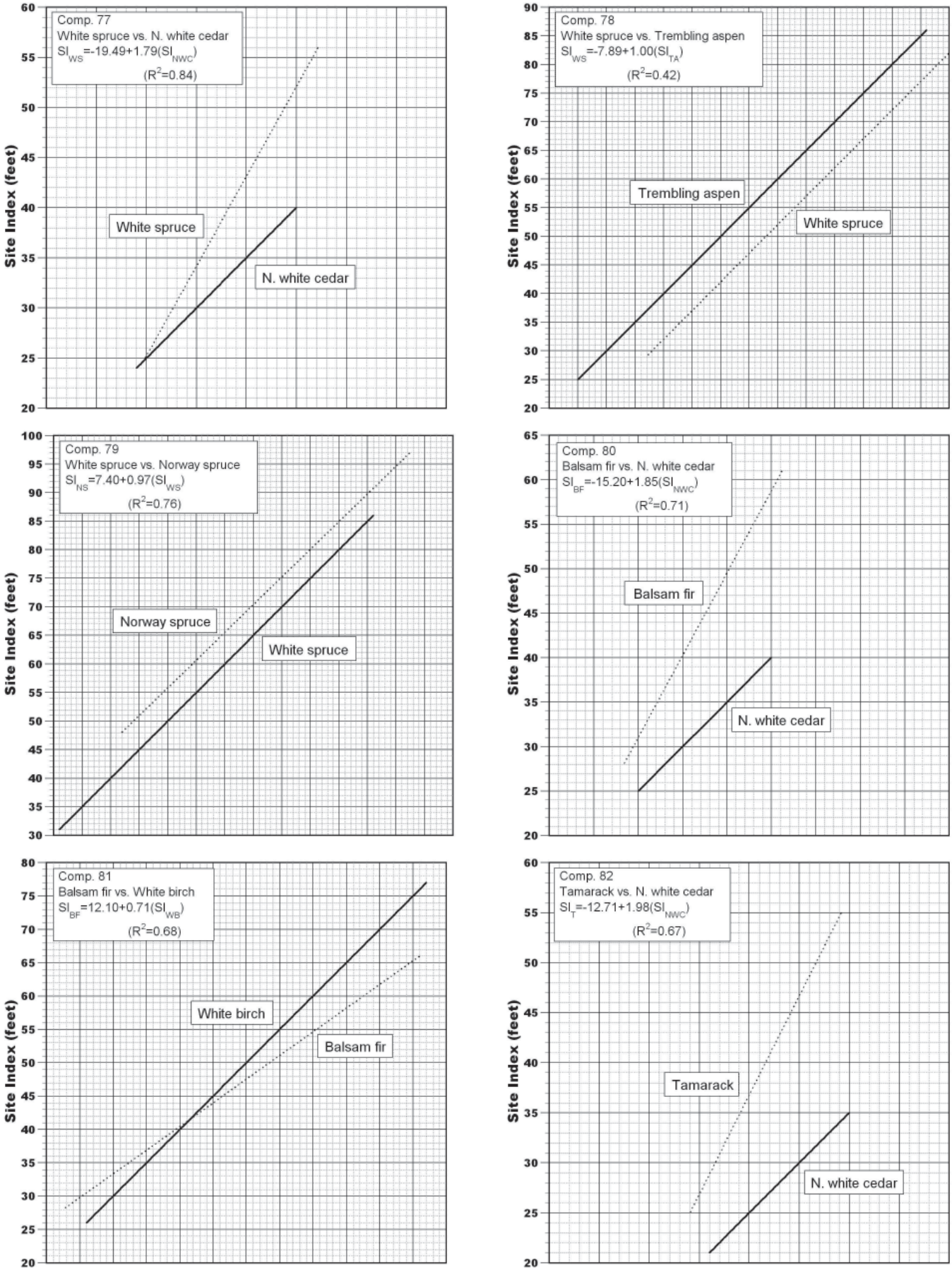

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RESULTS

The six separate and independent studies produced linear regression models expressing site index relations between 82 paired combinations of hardwood and conifer tree species in the Upper Great Lakes area (Tables 1 and 2). Several of these six studies had regression models for the same paired species combinations, thus we were able to compare results between the studies for the same paired species combinations thus allowing us to select the most precise (largest R^2) models for use in the Upper Great Lakes area. For example, for the sugar maple versus red maple comparison (Table 1—comparison 1), results were available from two studies. We selected the northern Wisconsin and Upper Michigan model (Carmean 1979) because this study covered a wide range of observed site indices, had 89 carefully selected plots, dominant and codominant site trees in each plot were carefully selected, site index was based on stem analyses from these selected trees, and this study had excellent precision (R^2 = 0.79). This study had much better precision than the relatively poor precision (R^2 = 0.33) for the Carmean et al. (1981) model that only had 17 plots. Site index for this 1981 study was based only on total tree age and total height measurements and site index was estimated using older harmonized site index curves.

The 82 recommended models are indicated in Table 1 for each species comparison and average models for these recommended models are given in Table 2.[3] Generally the recommended models in Tables 1 and 2 were the most precise (largest R^2), were based on the greatest number of plots, and covered the widest range of site index. The alternative models from the other independent studies for the same paired species combinations were considered as separate and independent models useful for verifying the recommended models. Comparisons of trends shown by the recommended models (Table 1) with trends shown by the other verifying models showed that all trends were similar, therefore, giving confidence in the reliability of the recommended models.

[3] Ten of the recommended 82 comparisons in Table 2 are for models where precision (R^2) was improved using an added variable that expressed soil drainage.

Figure 1, comparison 4 (Comp 4) illustrates how to use site index comparison graphs. Suppose you would like to estimate site index for American basswood in a sugar maple stand. For this stand, total height and total age measurements from several dominant and codominant sugar maple trees indicate that estimated site index for sugar maple is 60 feet; site index curves for sugar maple (Carmean 1978) are used for this direct site sugar maple index 60 estimation. In Figure 1, comparison 4, arrows illustrate that you start at 60 feet on the site index scale and then read right to the sugar maple line, then read up to the American basswood line, then read left back to the site index scale where site index for American basswood is estimated as 65 feet.

The reverse of this procedure also can be used in a stand where height and age measurements from American basswood trees indicate that American basswood has a site index of 65 feet. Using Figure 1 (comparison 4) we estimate that site index 65 feet for American basswood indicates that estimated sugar maple has a site index of 60. This example illustrates that the average model (Table 2—comparison 4) can be used forward or backward for estimating site indices for either basswood or sugar maple.

DISCUSSION

Study Methods

Large differences in precision are evident among the six studies (Table 1). The northern hardwood study (Carmean 1979) usually had models with very precise results (large R^2 values), but the two studies based mostly on forest survey data (Carmean and Vasilevsky 1971, Carmean and Hahn 1981) usually had models with less precise results (small R^2 values).

Reasons for the excellent precision for the northern hardwood study (Carmean 1979) are: (i) plots were located in carefully selected areas having similar soil and topography; (ii) plots had similar older, even-aged, fully stocked, undisturbed, hardwood stands; (iii) site trees on each plot were carefully selected so that only free-growing, undamaged dominant and codominant trees were used; (iv) stem analyses from two or more site trees for each tree species on each plot were used for developing individual tree height-age curves that then

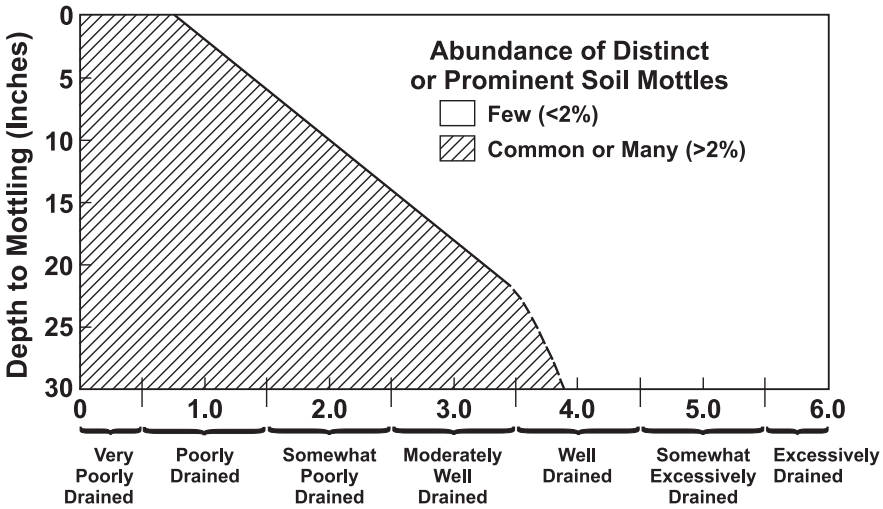

Figure 2.—Soil drainage classes can be estimated based on depth to a soil horizon having common or many mottles (Carmean 1979—adopted from USDA 1975).

were used for direct observation of site index; (v) for each of the species comparisons a large number of plots covering a wide range of site index were available for regression analysis; and (vi) improved precision for 10 hardwood species comparisons was gained by adding an independent variable expressing soil drainage.

In contrast, the two studies based mostly on forest survey data (Carmean and Vasilevsky 1971, Carmean and Hahn 1981) usually had models with poorer precision (smaller R^2). Reasons for poorer precision are: (i) forest survey plots were randomly located, thus many plots had to be rejected because they were in partially cut or poorly stocked stands, were in uneven-aged stands, or were in very young stands. We screened plot data attempting to reject such plots, however, a few less desirable plots might have been retained in the forest survey data set; (ii) some of the dominant and codominant site trees used on the forest survey plots might have suffered from past suppression and crown injuries thus such trees may not have been suitable for accurate site index estimation; (iii) tree ages were based on field examination of increment cores but accurate ring counts in the field often are difficult for diffuse porous tree species such as the aspens, white and yellow birch, and American beech; (iv) site index estimations were based on older harmonized site index curves (Carmean et al. 1989) that may not accurately express polymorphic tree-height growth patterns. Site index estimates from such harmonized site index curves might have particularly large errors for very old or very young trees, or for very good or very poor levels of site index; and (v) most of these older harmonized site index curves were based on total tree age rather than on breast-height age, thus precision of site index estimation is reduced because of slow and erratic early height growth before trees reached breast height.

Despite these many shortcomings, the two studies based on forest survey data (Carmean and Vasilevsky 1971, Carmean and Hahn1981) produced general results (Tables 1 and 2; Figure 1) that are still useful until more precise studies are made based on stem-analysis data from carefully selected plots, and from carefully selected dominant and codominant trees. The older Carmean and Vasilevsky (1971) study still has two recommended models (Table 1—comparisons 40 and 58); the larger Carmean et al. (1981) study still has 19 recommended models (Table 1).

Effects of Drainage

The northern hardwood study (Carmean 1979) produced regression models and graphs for 51 site index species comparisons having large R^2 values (Table 1, Figure 1). This table also shows that precision for 10 of these models could be further improved when a drainage variable was added to the regression model.

Figure 2 illustrates that this drainage variable was constructed using depth to common or many soil mottles; a linear transformation provided a numerical code for representing depth to such mottles. We found that changes in soil drainage are associated with changes in site index for 10 species comparisons, and the

magnitude of these site index changes associated with drainage differed for different tree species.

For example site index improvement with improved drainage was statistically significant but the magnitude of improvement was small for the sugar maple versus red maple comparison as well as for the sugar maple versus yellow birch comparison (Table 2—comparisons 1a and 2a). This indicates that sugar maple, red maple, and yellow birch have similar site indices on better drained soils (drainage classes 5, 4 and 3), but on somewhat poor (drainage class 2) and poorly drained soils (drainage class 1) red maple and yellow birch have slightly higher site indices than sugar maple.

But improved drainage has a major effect on the precision and site index differences for some paired species combinations. For example, for the yellow birch versus black ash comparison (Table 2 and Figure 1—comparison 28a) adding the drainage variable improved precision from R^2=0.61 to R^2=0.80; for the American elm versus black ash comparison (Table 2 and Figure 1—comparison 42a) the drainage variable improved precision from R^2=0.65 to R^2=0.78. The comparison graph (Figure 1—comparison 28a) shows that when growing together on poorly-drained soils (drainage class 1) black ash and yellow birch have similar relatively poor site indices. However, as drainage improves (drainage classes 2, 3, and 4) site indices are better for black ash than for yellow birch site indices. The comparison graph (Figure 1—comparison 42a) indicates that when growing together on poorly drained and somewhat poorly drained soils (drainage classes 1, 2, 3) American elm and black ash have relatively similar site indices, but on well drained soils (drainage class 4) site indices for black ash are much better than site indices for American elm.

Site Index Comparisons for Hardwood Species

Results (Table 1, Figures 1 and 3) show that the aspens have the highest site indices and American beech has the lowest site indices when compared to other hardwood species. Sugar maple, red maple, and yellow birch have relatively similar site indices (Table 2 and Figure 1—comparisons 1, 2, 14), but these three species usually have higher site indices than American beech and lower site indices than more intolerant hardwood species that include American basswood, American elm, white ash, black ash, northern red oak, black cherry, and white birch. Bitternut hickory was not included in the Carmean (1979) study but Dillabough's (1983) study (Table 2 and Figure 1—comparison 13) shows that bitternut hickory in southern Ontario grows exceptionally well on good sites.

The site index comparison models indicate four major hardwood site index groupings:

1. ***Low site index class***. American beech consistently has much lower site indices than other associated hardwood species (Table 2 and Figure 1—comparisons 3, 15, 24)
2. ***Medium site index class***. Sugar maple, red maple, and yellow birch have similar site indices (Table 1 and Figure 1—comparisons 1, 2, 14) but each of these three species consistently have higher site indices than American beech (comparisons 3, 15, 24). However, when site indices for these three tree species are compared to site indices for more intolerant hardwood species such as American basswood, American

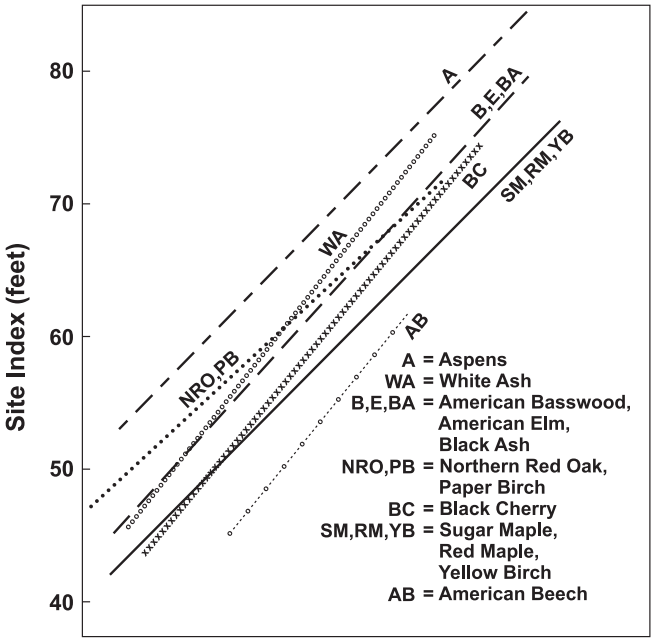

Figure 3.—Site index comparison graph showing site index relations between groupings of northern hardwood forest species in northern Wisconsin and Upper Michigan (Carmean 1979).

elm, white ash, black ash, black cherry, northern red oak, and white birch, we find that they consistently have lower site indices than for the more intolerant hardwoods (Table 2 and Figure 1; for sugar maple comparisons 1 to 13; for red maple comparisons 16 to 23; for yellow birch comparisons 25 to 32).

3. ***High site index class.*** This class includes several relatively intolerant hardwood species such as American basswood, American elm, white ash, black ash, black cherry, northern red oak, and white birch. These more intolerant species have consistently higher site indices than sugar maple, red maple, and yellow birch, but have consistently lower site indices than the aspens (Table 2 and Figure 1:—for American basswood comparisons 4, 16, 25, 39, 40; for American elm comparisons 5, 17, 26, 46; for white ash comparisons 7, 19, 28; for black ash comparisons 7, 19, 28, for black cherry comparisons 12, 21, 30, 44; and for northern red oak comparisons 8, 20, 29).

   But trends sometimes differ among these rapid-growing intolerant hardwood species. For example, white ash on very good sites has higher site indices than all other hardwood species except the aspens (Table 2 and Figure 1—comparisons 34, 41, 47 to 50). In contrast, northern red oak and white birch on poor sites have higher site indices than all hardwood species other than the aspens (Table 2 and Figure 1:—for northern red oak comparisons 38, 45, 49, 51, 57 to 60; for white birch comparisons 38, 45, 49, 57, 60). These variations among species in the ***high site index class*** prompted separating these relatively intolerant hardwood species into four subgroups: (a) white ash; (b) American bassswood, American elm, and black ash; (c) northern red oak and white birch; and (d) black cherry.

4. ***Very high site index class.*** The aspens consistently have much higher site indices than all other associated hardwood species (Table 2 and Figure 1—comparisons 10, 11, 23, 32, 39, 46, 50 to 56, 58 to 62, 67, 73, 76, 78).

Multiple species comparison graphs also were constructed (Figures 4 to 7) illustrating site index differences between various hardwood and conifer species in the Upper Great Lakes area. These multiple species comparison graphs are for illustrative purposes only and the actual paired species models and graphs (Table 2, Figure 1) are recommended for site index estimation purposes.

Site Index Comparisons for the Aspens

We expanded on the results from the earlier northern hardwood study (Carmean 1979) with further details (Carmean and Hahn 1981) about site index relations between trembling aspen and bigtooth aspen as well as relations between the aspens and northern hardwood and conifer species. Site index comparisons between the aspens showed that bigtooth and trembling aspen have similar site indices for all levels of site index (Table 2 and Figure 1—comparison 61). Trembling aspen consistently have higher site indices when compared to balsam poplar (Table 1 and Figure 1—comparison 62). Both bigtooth and trembling aspen consistently have higher site indices when compared to other hardwood species at all levels of site index (Table 2 and Figures 1, 5, and 6).

Comparisons between the aspens and conifer species also shows that the aspens consistently have higher site indices than the conifers (Table 2 and Figure 1—comparisons 67, 73, 76, 78; Figure 7). However, only a few of those comparisons have aspen site indices less than 40 feet. Reasons for this lack of poor-site aspen plots are indicated in studies for northwest Ontario where few merchantable trembling aspen stands occur on poor sites such as dry sands, shallow to bedrock morainal soils, or poorly drained soils (Carmean 1996, Carmean and Li 1998, Carmean et al. 2006). Trembling aspen may regenerate on these poor sites but defect and early “stand breakup” occurs, thus few older merchantable aspen stands are found on such poor sites. For relatively poor sites, bigtooth aspen and white birch have similar site indices, but on good sites bigtooth aspen has much higher site indices than white birch (Table 2 and Figure 1—comparison 59). Likewise for relatively poor sites, trembling aspen and jack pine have similar site indices but for better sites trembling aspen site indices are higher than jack pine site indices (Table 2 and Figure 1—comparison 67; Figure 7).

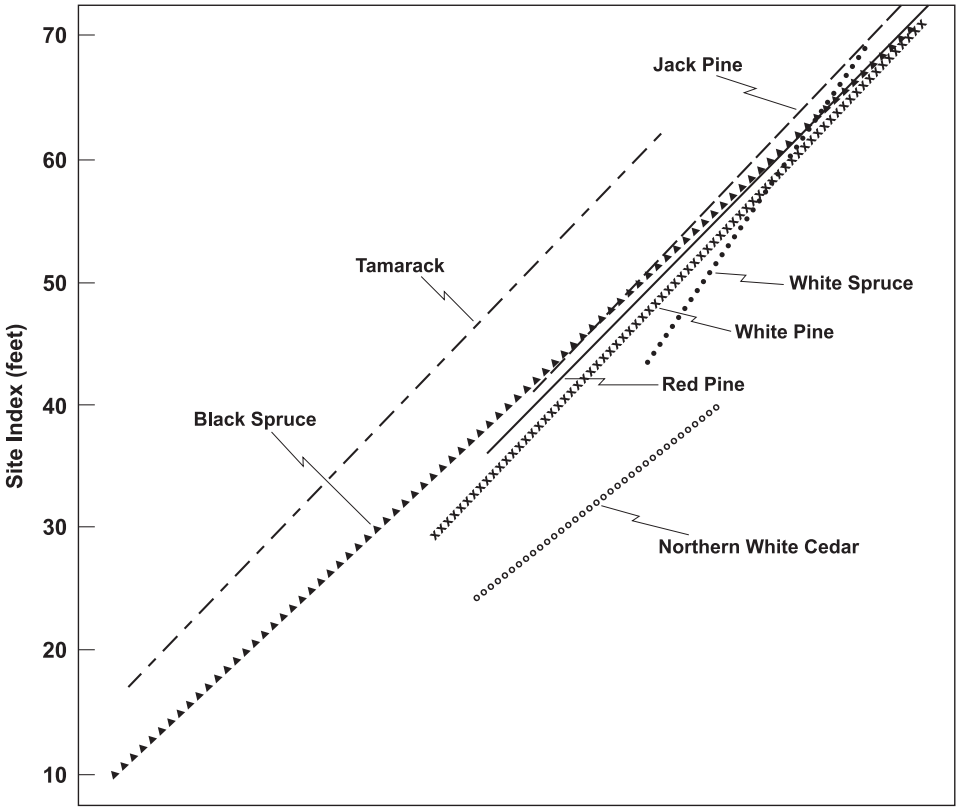

Figure 4.—Multiple species site index comparison graph for conifer tree species in the Upper Great Lakes area. This graph was constructed using models 5, 69, 70, 75 and 77 (Table 2).

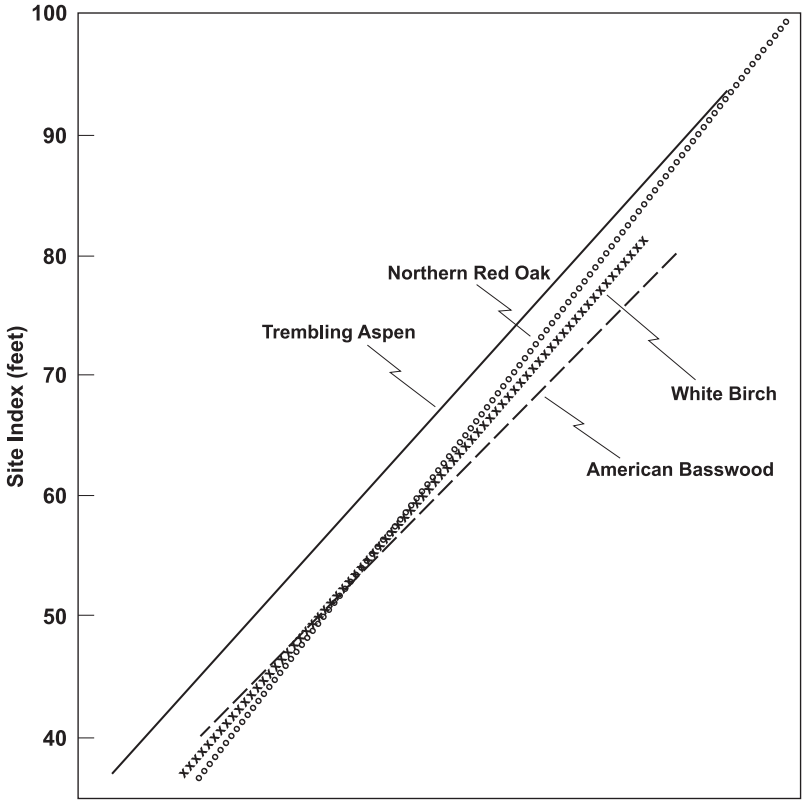

Figure 5.—Multiple species site index comparison graph for trembling aspen, white birch, northern red oak and American basswood in the Upper Great Lakes area. This graph was constructed using models 40, 54 and 58 (Table 2).

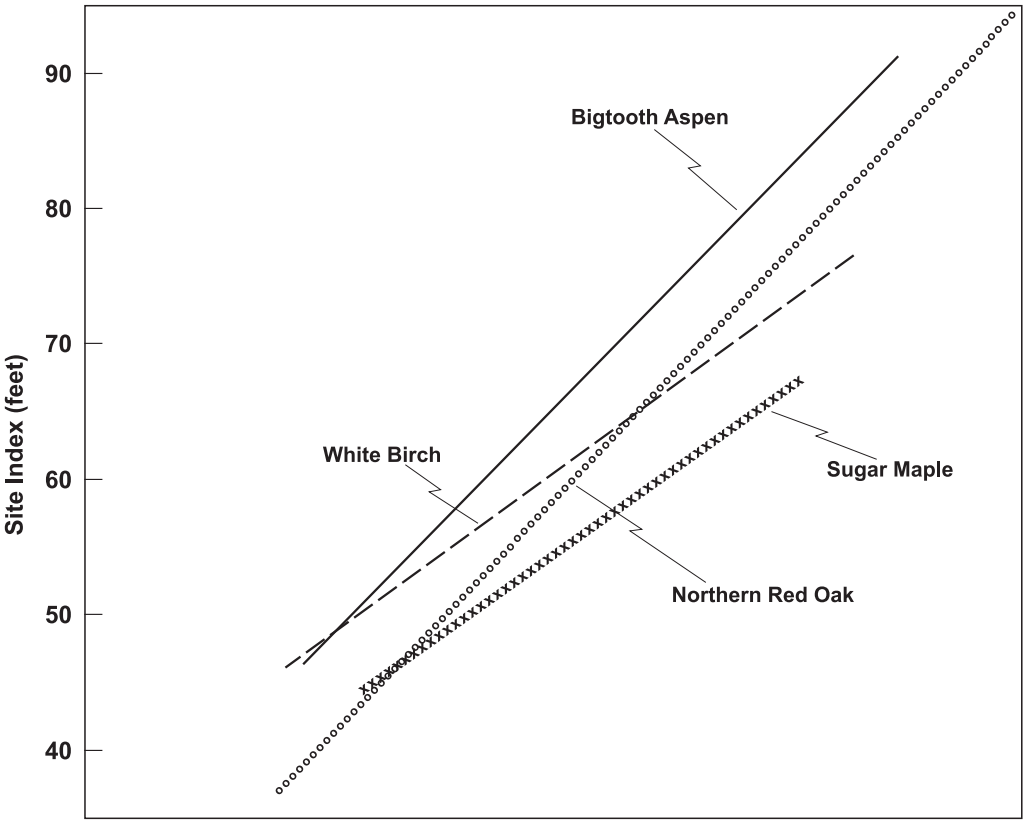

Figure 6.—Multiple species site index comparison graph for bigtooth aspen, white birch, northern red oak and sugar maple in the Upper Great Lakes area. This graph was constructed using models 11, 55 (Table 2).

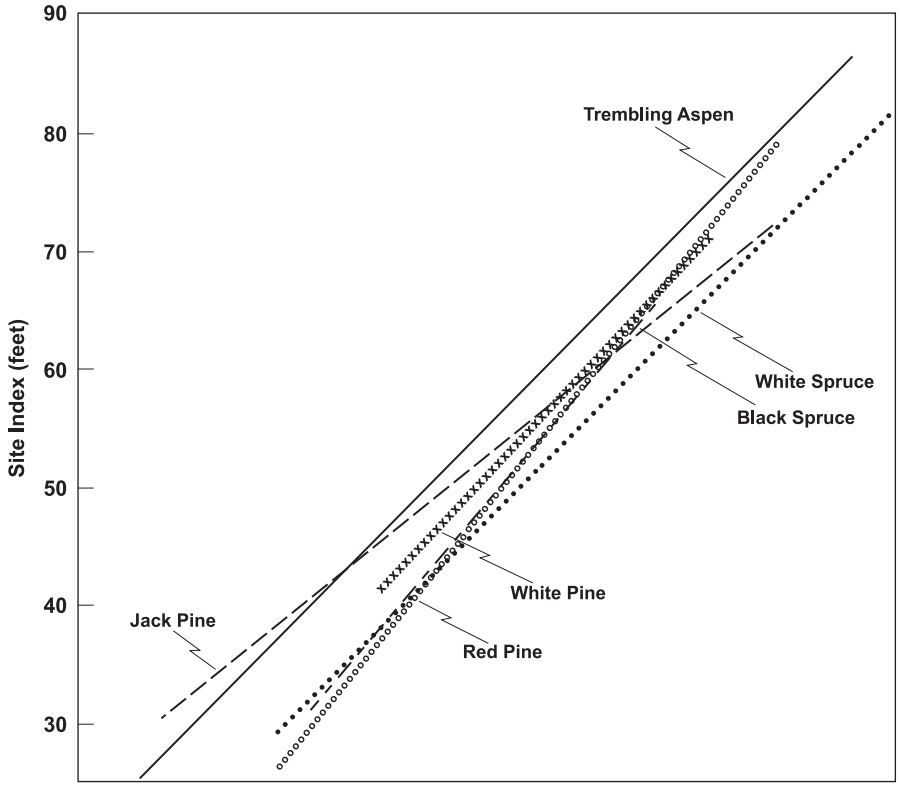

Figure 7.—Multiple species site index comparison graph for trembling aspen, jack pine, red pine, white pine, black spruce and white spruce in the Upper Great Lakes area. This graph was constructed using models 67, 73, 76 and 78 (Table 2).

Site Index Comparisons for Oak Species

Comparisons for oaks and yellow-poplar are summarized for the Central States (Carmean and Hahn 1983). Results from this northern study are similar to the Central States study where we show that northern red oak consistently has higher site indices than white oak (Table 2 and Figure 1—comparison 53). Northern red oak usually has lower site index than the aspens (Table 2 and Figure 1—comparisons 54, 55), but has higher site indices than sugar maple, red maple, and yellow birch (Table 2 and Figure 1—comparisons 8, 20, 29, 87).

Site index comparisons for conifers

Tamarack consistently has much higher site indices than other conifers (Table 2 and Figure 1—comparisons 66, 75, 82; Figure 4). In contrast, northern white cedar consistently has much lower site indices than the other conifers (Table 2 and Figure 1—comparisons 77, 80, 82; Figure 4). We found that site indices are relatively similar for jack pine, red pine, white pine, black spruce, and white spruce (Table 2 and Figure 1—comparisons 65, 65, 69). Norway spruce plantations in southern Ontario consistently has higher site indices than white spruce plantations (Table 2 and Figure 1—comparison 79); excellent growth for Norway spruce is indicated by site index curves for Norway spruce plantations in southern Ontario (Gordon et al. 1989), and in central New York (Jokela et al. 1988).

YIELD AND VALUE COMPARISONS

The six site index comparison studies summarized in this report have produced a wealth of information comparing site index relations among 24 hardwood and conifer species in the Upper Great Lakes area. This information when combined with yield tables, yield models, and product value estimates will assist in deciding which tree species is most productive and economically more desirable for management on forest lands having different levels of site index. However, we should recognize that site index comparisons are only comparisons of dominant and codominant tree heights at 50 years. Therefore estimating site index is only the first step for determining the most productive and commercially valuable tree species for each site; the next step should be using these site index estimates to enter yield tables and yield models for estimates of potential yield and potential product values for alternative tree species at various ages as well as yields and product values at different levels of site index.

Site index (tree height) comparisons, while indicative of potential yield differences, also should be accompanied by yield and product value comparisons for each species at different levels of site index. For example, Table 2 and Figure 1, comparison 64, indicate that jack pine has slightly higher site index than red pine. However, when site index estimates for jack pine and red pine are related to yield tables (Plonski 1974), we find that red pine has much greater yield than jack pine at the same level of site index. The reason for this much greater yield is that fully stocked red pine stands have much higher basal areas than fully stocked jack pine stands (Alban 1978). Red pine also is longer-lived than jack pine thus red pine maintains height, diameter, and basal area growth better than jack pine. Therefore, yield differences would be even greater when yield comparisons are made between red pine and jack pine at older ages (Carmean and Thrower 1995, Lundgren 1982).

Comparisons of product values also favor red pine because older red pine stands on good sites usually have considerable volume in valued saw logs, veneer logs, cabin logs, and utility poles while, in contrast, older jack pine stands usually have smaller volumes of these valuable products. Accordingly, product value comparisons also are needed in addition to tree height (site index) and yield comparisons. Thus tree species that can produce valuable veneer and saw logs might be preferred on certain sites even though height, site index, and biomass yield might be less than the site index and yields produced by rapid growing short-lived species such as aspen that are utilized mostly for less valuable pulp and fiber.

Tree height and volume growth before and after site index age also should be compared. Certain short-lived species such as the aspens may grow rapidly in early years, thus at 50 years (site index age) are usually taller and stands have greater volumes when compared to stands of longer-lived species that have slower early height growth such as red pine and white pine. But red pine and white

pine maintain height, diameter, and volume growth and eventually these species will be taller and will have more volume and greater values than aspen. Accordingly, these pines will have higher site indices, greater yields, and greater values than aspen if 100 years was used as site index age rather than 50 years.

We now have the means for developing comparative yield and comparative value models for alternative tree species growing on different sites. Comparative models based on site index, yield, and commercial value can provide tools for determining which species of tree is the most productive and commercially desirable for each level of site quality in the Upper Great Lakes area.

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APPENDIX I.

Scientific and common names of tree species (Little 1953)

Scientific name	Common name
Abies balsamea (L.) Mill.	Balsam fir
Acer rubrum L.	Red maple
Acer saccharum Marsh.	Sugar maple
Betula alleghaniensis Britton	Yellow birch
Betula papyrifera Marsh.	White birch
Carya cordiformis (Wangenh.) K. Koch	Bitternut hickory
Fraxinus americana L.	White ash
Fraxinus nigra Marsh.	Black ash
Larix laricina (Du Roi) K. Koch	Tamarack
Liriodendron tulipifera	Yellow-poplar
Picea abies (L.) Karst.	Norway spruce
Picea glauca (Moench) Voss	White spruce
Picea mariana (Mill.) B.S.P.	Black spruce
Pinus banksiana Lamb.	Jack pine
Pinus resinosa Ait.	Red pine
Pinus strobus L.	Eastern white pine
Populus balsamifera L.	Balsam poplar
Populus grandidentata Michx.	Bigtooth aspen
Populus tremuloides Michx.	Trembling aspen
Prunus serotina Ehrh.	Black cherry
Quercus alba L.	White oak
Quercus rubra L.	Northern red oak
Thuja occidentalis L.	Northern white cedar
Tilia americana L.	American basswood
Ulmus americana L.	American elm

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This report summarizes six studies that compare site index relations between 24 hardwood and conifer species in the Upper Great Lakes area of the United States and Canada. These six studies have many regression models and graphs for comparing site index between forest species thus providing tools for estimating site index for alternative tree species based on direct site index measurements using tree species actually present in forest stands. Thus the objective of this summary paper is to summarize these models so that we can provide the most accurate tools available for estimating the tree species that are most productive and economically valuable for management on each forest site.

KEY WORDS: height growth, predicting most productive tree species

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