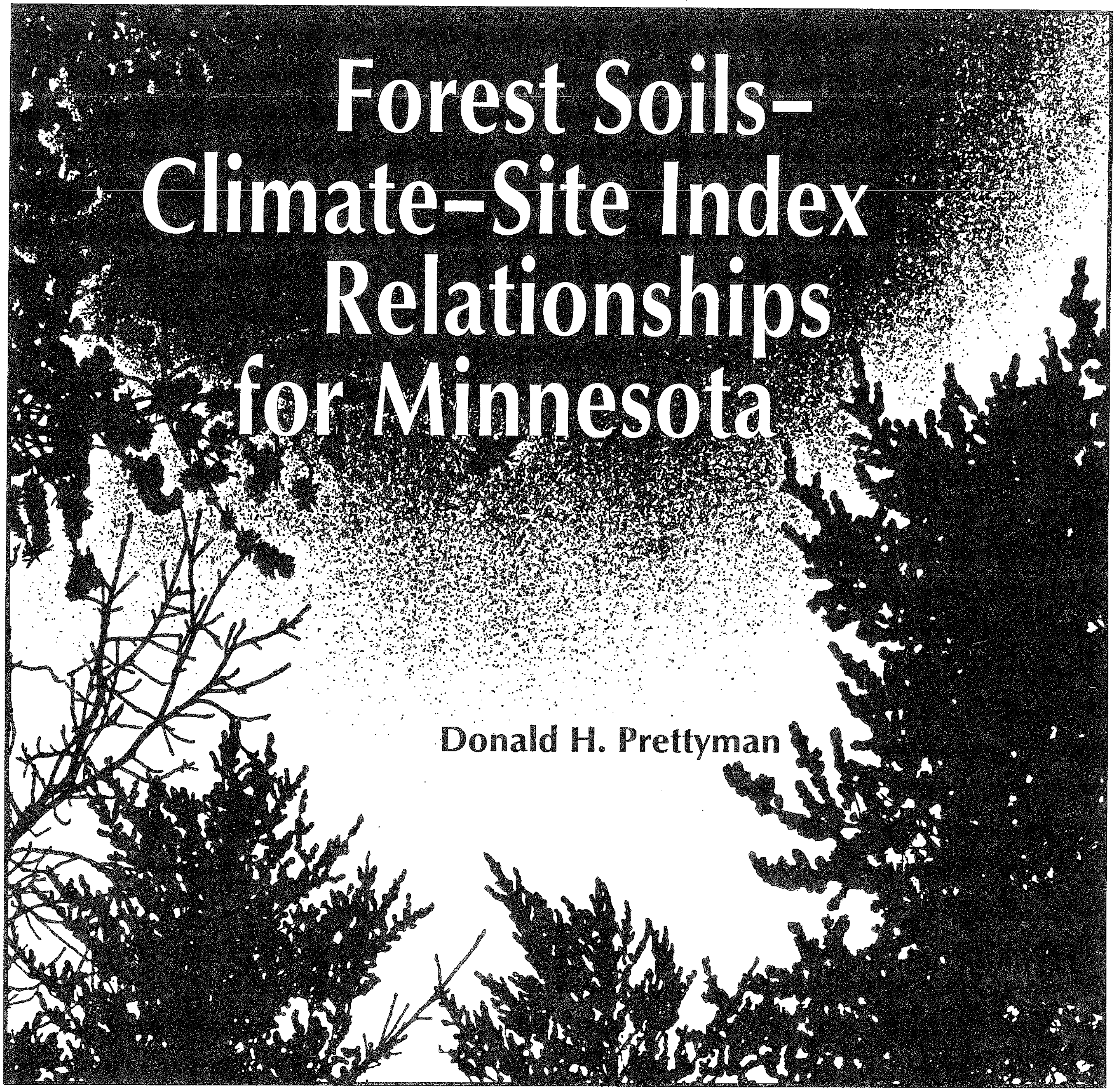

Forest Soils–Climate–Site Index Relationships for Minnesota

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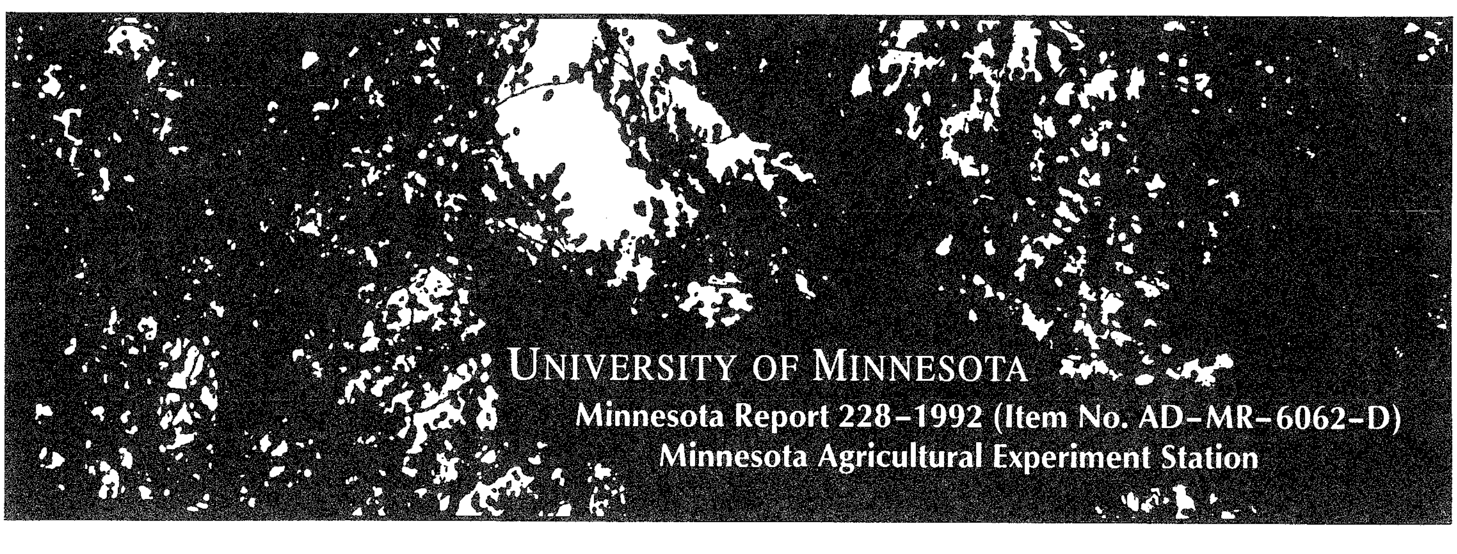

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Forest Soils–Climate–Site Index Relationships for Minnesota

Donald H. Prettyman

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Minnesota Agricultural Experiment Station
University of Minnesota

St. Paul, Minnesota

Author

Donald H. Prettyman is a forest soil scientist at the Cloquet Forestry Center, Department of Soil Science and Minnesota Agricultural Experiment Station, University of Minnesota.

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FOREST SOILS–CLIMATE–SITE INDEX

Relationships for Minnesota

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I. INTRODUCTION

This report summarizes selected forest soil, site index, and climate information collected by agencies participating in forest resource inventories in Minnesota. Owners and managers of forests within Minnesota should find this report helpful for developing a better understanding of tree growth as influenced by forest soils and climate. It should help them prepare improved management options for Minnesota's principal tree species.

Educators may find this report to be useful as background for integrating elements of forest environments. They and other readers may also gain a better understanding of selected elements of the environment and the influence of those elements on site index.

Site index information in this report relates to a direct method of determining a tree's response to a specific environment. Forest soil and climate information represent elements of an indirect method.

Site index is based on the relationship between tree age and height. An example is a tree fifty years old and fifty feet tall having a site index of fifty. Any element in the environment that affects height growth will likewise affect site index.

Site index reflects both genetic factors and an integrated response of trees to an environment (Monserud and Rehfeldt 1990). Such an index is commonly used for estimating site quality. A tree can be considered an integrator of temporal environmental conditions. Relationships between climate, forest soils and site index are presented in this publication.

Most forest soil information is a product of the Minnesota Cooperative Soil Survey (MCSS). Site index information includes data from the Minnesota Department of Natural Resources' Cooperative Stand Assessment (CSA) and Forest Inventory and Analysis (FIA) and from the MCSS. All climate information is from electronic programs and publications of the Department of Soil Science, University of Minnesota, and the State Climatology Office, Minnesota Department of Natural Resources.

Both the CSA and FIA information sets are the products of statistically designed projects. Each has thousands of tree measurements from throughout Minnesota. Determining actual volumes in current stands is the objective of the CSA. CSA includes both highly productive and marginal stands for common tree species. FIA is part of a national permanent plot system which has the objective of evaluating temporal and spatial changes in species and volume relationships.

MCSS information is produced by a subjective selection of sites from which forest soil and tree site index data are collected. Some of that information reflects an attempt to determine potential tree growth for each soil by measuring trees which are believed to best represent non-suppressed growth.

Precipitation, temperature, and other climate information are collected from several hundred stations throughout Minnesota. Records for most stations span at least 40 years. Those stations include sites located in a variety of environments, including forests. Event-oriented flash flood analyses and summaries directed at plant growth are also available. Examples of the latter are duration of frost free days and growing degree days.

A few basic statistical summaries of the information that has been collected are included in this report. Due to the variation of sources and methods used for data collection, no elaborate statistical methods are used to analyze the data.

II. BACKGROUND

CLIMATE

Minnesota's climate ranges from cool boreal forest conditions in the northeast to warmer, drier, and windy tall-grass prairie in the west, to the warm and more humid climate in the southeast. Local features such as Lake Superior create variations in the climate. Ridge and valley terrain in southeastern Minnesota have distinct aspect and slope gradient features which are generally lacking in the remainder of the state. See table 1 and figure 1 (D. G. Baker et al. 1967) and figure 2 (D. G. Baker et al. 1985) for additional climate information.

Table 1 summarizes climate information, beginning in the northern part of Minnesota (Grand Marais) and continuing through southern Minnesota (Caladonia). Figure 3 shows the location of each station, with numbers coded to the stations shown in table 1.

Annual patterns of precipitation and temperature are evident in figures 1 and 2. For precipitation there are distinct patterns from north to south and from east to west. Temperatures show a clear pattern of increase from north to south. Growing degree days (GDDs–base 40° F) are shown in figure 4 (Baker et al. 1985).

All climate data cited in this publication comes from records of representative weather stations located throughout Minnesota. There are substantial differences among the environments represented by those stations.

Examples of these differences include

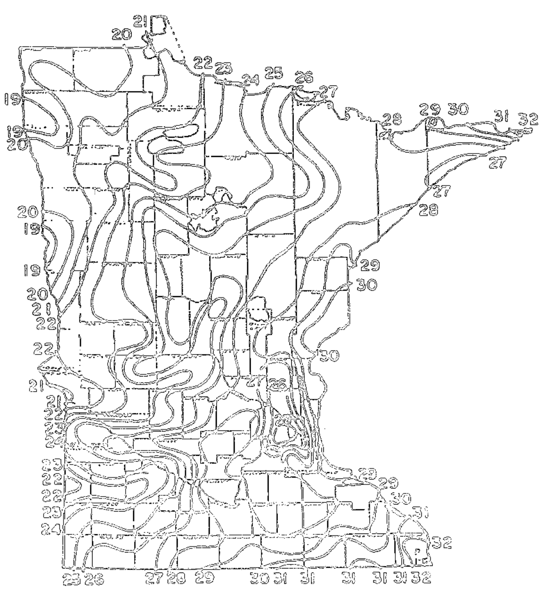

Figure 1. Annual precipitation in inches, Minnesota. In general, precipitation increases from the extreme northwest corner to the southeast with a secondary maximum in the northeast and a secondary minimum in the southwest.

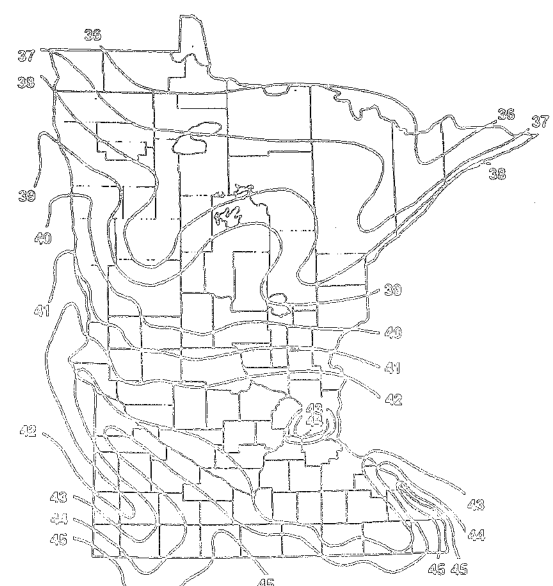

Figure 2. Annual normal temperatures (°F).

Table 1   Climate Information: precipitation, growing degree days and temperature means.

Station	Map Code	Precipitation (inches) annual	Precipitation (inches) May-August	Growing Degree Days (40° F base)	Temperatures (degrees F) annual	Temperatures (degrees F) May-August
Grand Marais	1	26.3	12.2	2,581*	38.6	55.3
Isabella	2	30.4	15.0	3,000*	36.7	59.1
Two Harbors	3	28.0	14.4	3,198	40.1	58.3
Cloquet	4	29.0	14.9	3,126	39.1	60.8
Baudette	5	25.6	13.8	3,469	36.9	60.9
International Falls	6	24.7	13.0	3,074	37.1	60.9
Hibbing	7	24.9	13.9	3,400	37.3	60.1
Virginia	8	27.3	14.5	3,544	38.7	61.6
Hoyt Lakes	9	28.1	14.9	3,100	36.3	58.9
Duluth	10	30.3	15.0	3,168	38.3	59.7
Grand Rapids	11	25.6	13.9	3,480	39.4	62.1
Walker	12	26.2	15.4	3,771	40.3	63.2
Park Rapids	13	25.7	14.7	3,649	38.9	62.8
Detroit Lakes	14	24.7	14.8	3,745	39.0	63.0
Fosston	15	22.4	12.8	3,700*	39.4	63.4
Wadena	16	25.8	14.6	4,006	40.4	64.0
Brainerd	17	26.5	15.1	3,945	40.2	63.8
Aitkin	18	28.7	16.0	3,750*	40.4	63.4
Moose Lake	19	28.3	15.7	3,266	39.8	62.5
Cambridge	20	27.9	15.2	4,074	42.2	65.3
Zumbrota	21	28.2	14.7	4,560	44.6	66.5
Winona	22	31.4	16.3	5,018	46.2	68.1
Caledonia	23	34.1	16.7	4,900	44.2	65.8

* Value is from State map.

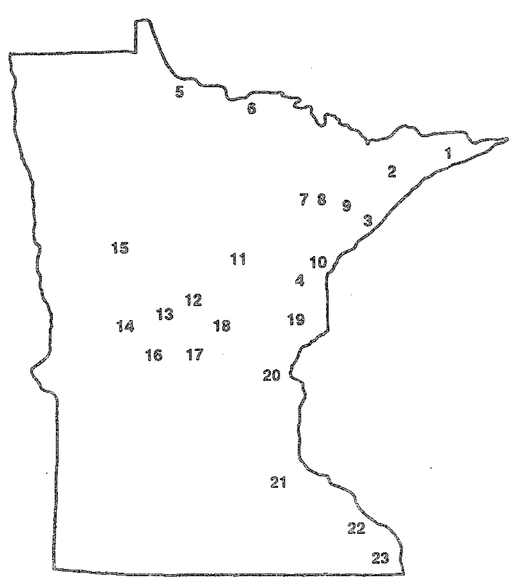

Figure 3. Locations of Minnesota weather stations which provided data used in this report. Codes key to weather station list in table 1.

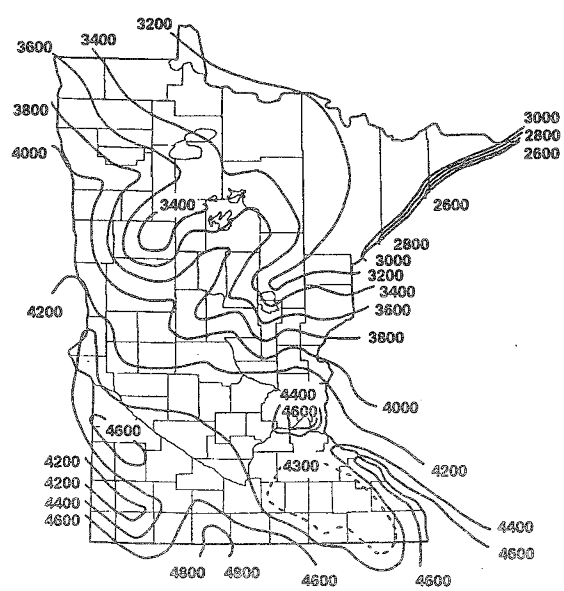

Figure 4. Normal total annual growing degree days, T = 40°F, corrected to an 8 a.m. observation.

International Falls, which has a mean annual precipitation of 25 inches, and Winona, which has 31 inches. The former has 3,469 GDDS compared to 5,018 for the latter. Caledonia, thirty air miles south of Winona, has 34 inches of annual precipitation. Duluth's airport receives about 30 inches of annual precipitation and has 3,168 GDDS compared to 29 inches and 3,750 GDDS for Aitkin which is about eighty air miles west of Duluth. Compared to those, Detroit Lakes has 25 inches of precipitation and 3,745 GDDS.

Duration of snow cover in Minnesota (Kuehnast et al. 1982) ranges from 30–130 days for a depth of six inches and 0–30 days for more than 24 inches. Snow cover affects recharge of soil moisture and frost depth, pattern, and duration. Those elements affect the temperature in the root zone and will affect the length of season for conditions favorable for root development and growth.

SOILS

Soils range from fertile loess capped and prairie soils in the southeast to lime rich silty and clayey soils of the Red River Valley to the extensive acid peat bogs in north central Minnesota and the thin drift soils in the bedrock-dominated terrain in the northeast. Sixteen million acres of forest occur over that wide range of soil conditions.

Geologists (Sims and Morey 1972 and Hobbs and Goebel 1982) report that most of Minnesota is glaciated except for the highlands in the southeast where only the valleys of major streams have glacial materials. Glacial materials are more than 9,000 years old, and some of the oldest soil parent material is the remains of weathered bedrock in southeast Minnesota.

SOUTHEASTERN MINNESOTA

Southeastern Minnesota has some of the oldest land features in the state. Thick leached and weathered remains of bedrock form the parent material for many soils in the broken, sloping landscape. Commonly, the wind-deposited loess is the richest portion of the root zone. Landscape position is potentially an important site factor. Many of the richest sites are found in the lower slope benches and moist coves.

NORTH CENTRAL MINNESOTA

Glaciated conditions prevail in north central Minnesota. Materials from three glacial sources and several glacial lakes make this area unique. Glaciers moving into the area from the northwest carried nutrient rich grayish materials containing limestone and shale pebbles from the lime and clay-rich sedimentary bedrocks and older glacial debris common in the Red River Valley. Soils formed in these materials are some of the most productive in the area. That productivity is based on the high level of lime, nutrients and water holding capacity in many root zones.

A second glacial lobe moved into the area from the east and northeast out of the Lake Superior basin carrying reddish materials containing agates and volcanic rock pebbles. Some of these materials are rich in clay. They have medium levels of nutrients and medium to high moisture holding capacity. Soils developed in this parent material are somewhat less productive than those formed in the grayish material.

The third glacial lobe, from the northeast, deposited materials derived from the nutrient poor bedrock and older glacial materials typical of the Canadian Shield and boreal forest. Soils formed in this parent material, which is rich in granitic and other igneous rock pebbles, are loamy and sandy. These soils are low in nutrients and moisture holding capacity.

NORTHWESTERN MINNESOTA

In the northwestern part of Minnesota, glacial material deposited by ice moving into the area from North Dakota and Canada is the parent material for the lime rich gray silty and clayey soils common in the area. Many of the soils which developed in the deposits of Glacial Lake Agassiz are laden with silt and clay and generally lack gravel.

Nutrient rich root zones with medium to high moisture holding capacity are generally quite favorable for tree growth, but the region's climate limits full use of those soil resources. In this area the forests give way to the east boundary of the prairie which extends to the Rocky Mountains.

NORTHEASTERN MINNESOTA

Northeastern Minnesota has glacial materials dominated by ice movement from the Canadian Shield, Lake Superior basin, and northern and northwestern Minnesota. Those materials are typically sandy, acidic and laden with igneous rock fragments, and they form a shallow cover over nutrient-poor igneous bedrock. Brown and gray colors dominate the materials.

Soils developed in this material have low amounts of nutrients, low moisture holding capacity, and high gravel content. Those properties couple with a short growing season to result in slow tree growth. A major portion of this area is also greatly influenced by the boreal forest environment whose southern boundary is in this area.

Materials from the Lake Superior basin are reddish and brownish and vary from sandy and loamy deposits laden with weathered volcanic stone and gravel to red clay-rich stone free deposits. The former have medium nutrient and moisture holding capacity and present considerable restrictions for root development and growth. In contrast, the clayey material is rich in nutrients, has a high moisture holding capacity and is relatively stone free. Tree growth associated with those basin deposits is varied and effected by a short growing season and the local effects of Lake Superior.

Deposits from Glacial Lake Agassiz and ice flow from the northwest occur in the western portion of northeastern Minnesota. Most of this material was deposited by ice and has a varying amount of stone and gravel. A medium to high level of nutrients and moisture holding capacity supports moderate to rapid tree growth for selected species. Lake Agassiz deposits are rich in lime, nutrients, silt and clay. They are commonly stone free, have a high moisture holding capacity and support rapid tree growth for selected species.

FOREST

Because of the varied climate in Minnesota, the state's forest can be quite complex. In southeast Minnesota, forest composition is similar to the oak and hickory forest farther south in the cornbelt. Included in this area are some of the most productive forests in Minnesota. High value black walnut is limited to this part of the state. The most rapidly growing red and white pine also occur in this area.

A mixture of maple, oak, aspen, and pine are common in the forest-prairie zone in western Minnesota. A virgin northern hardwood stand in Becker County and the near natural forest in much of Itasca State Park have national recognition and exemplify the nature of forests in the area prior to logging and settlement. Wet acid bogs typically support black spruce *(Picea mariana)* and other lowland conifers.

Aspen, red oak *(Quercus rubra)*, pines, and a limited amount of red maple *(Acer rubrum)*, sugar maple *(Acer saccharum)*, basswood *(Tilia americana)* and elm *(Ulmus* sp.*)* are found in the central and north central part of the state. Some of the most productive sites for selected species are found in this area. This area joins the prairie to the west and the boreal forest to the north and northeast.

Aspen, spruce, fir, and pine prevail in northeastern Minnesota. A band of northern hardwood forest occurs in the highlands along the north shore of Lake Superior. Native tamarack *(Larix laricina)* is common in wet lowlands. A limited amount of white cedar *(Thuja occidentalis)* is also found in the area, with the highest quality in the richer uplands. Wet acid peat bogs of several thousand acres occur in this area and support slow growing black spruce.

General forest production is lower in northeastern Minnesota than across the rest of the state. This results from the short growing season, generally low fertility, acid soils, and extensive areas of thin soils underlain with low fertility bedrock.

III. INFORMATION ANALYSES

FOREST INVENTORY ANALYSIS, COOPERATIVE STAND ANALYSIS, AND MINNESOTA COOPERATIVE SOIL SURVEY INFORMATION

This analysis includes presentations of both general geographical site index information and soil-species site index information. The discussion uses information that is commonly available on climate, geology, and soil, combining such data with site index information for the purpose of preparing exhibits that demonstrate the influence of biophysical elements on tree growth. Those elements are precipitation, temperature, growing degree days, soil series, laboratory analyses of soils, and glacial landforms.

Table 2 depicts a comparison of site index values from CSA, FIA and for all measurements for all species. A part of the differences in values is likely related to the different objectives for the respective projects. Also, for any given species

Table 2. Comparison of site index values for all species: Cooperative Stand Analysis versus Minnesota Cooperative Soil Survey versus Forest Inventory Analysis.

County	Source	Age mean	Site Index mean	max	min	Samples
Aitkin	CSA	62	56	95	< 30	9,913
	MCSS	59	70	114	26	1,413
	FIA	56	56	70	36	139
St. Louis	CSA	68	52	99	< 30	11,903
	MCSS	60	58	91	17	1535
	FIA	54	55	75	38	534
Houston	CSA	75	57	98	40	402
	MCSS	60	67	98	35	146
	FIA	75	52	85	35	56
Winona	CSA	69	60	99	36	769
	MCSS	70	66	94	35	127
	FIA	73	58	97	33	63

the number of measurements varies considerably between the three projects.

Mean site index values for MCSS are always higher than those for CSA or FIA. The margin of difference is greatest in Aitkin County and least in St. Louis County. A similarity between the CSA and FIA mean site index values is noted, though the number of samples is substantially different.

Table 3 compares the CSA, MCSS, and FIA site index information for selected species. Aitkin and St. Louis Counties are selected because of the amount of information available. Values in the table reflect site index data collected from environments common in each county. For general planning, the information from either county may suffice.

A comparison of the mean site index values for all data sets reveals little difference. In some instances, the values are identical. The results of this comparison may be helpful for determining an appropriate number of site index measurements necessary for producing reliable information. These results indicate that FIA information may be quite adequate for general planning. However, project stand planning would benefit from site specific data.

Site data may explain some of the differences between maximum and minimum values for each species. For example, some rapidly growing trembling aspen *(Poplus tremuloides)* are found in areas of nutrient-rich, fine texture soils which in some instances are quite moist. The highest site indexes are sometimes associated with soils rich in calcium. That information may be useful in developing management prescriptions for trembling aspen, such as for rotation ages and duration of quality growth. In contrast, some of the slower growing aspen are found in the areas with short growing season and soils with low fertility.

Comparing the maximum and minimum values may indicate the range in differences between environments that affect a given species. A kind of land classification system which stratifies the land based on environmental elements, including cultural elements, may be needed to explain the range in site index values for a given species in a particular area. Current stratification based on stand conditions or soil series does not appear to suffice. There are numerous articles in the literature that address that topic. Amending criteria for either may produce different results.

As an example, the site index for red pine *(Pinus resinosa)* growing in similar soils is higher in southwest (62) than in northern (55) St. Louis County. A statewide comparison of site index values for red pine growing in soils developed in glacial outwash and in contrasting climates shows these results: Houston County > Aitkin County > Clearwater County > St. Louis County > Lake County. Table 4 shows the site index and climate information for each County.

Red pine response to elements in the root zone also varies by regions of Minnesota. For example, in southeast Minnesota there is little difference in site index for red pine growing in sandy or silty soils. Both have a mean site index of 93. However, in northeast Minnesota as silt and clay increases from 20 percent or less to 65 percent in dry soils, the mean site index increases from 56 to 66.

With site index as the dependent variable the r2 value for each variable is precipitation 0.454, growing degree days 0.885, and mean summer temperature 0.649. For all variables with site index as the dependent variable, the r2 is 0.932. There is a clear correlation between red pine site index and growing degree days (base 40° F). Precipitation is significantly related to site index value differences between Aitkin and Clearwater Counties. A change also occurs somewhere between Virginia and Aitkin. Additional information for r2 values is included in the section for MCSS information.

A review of the climate information in table 1 also reveals a substantial difference between the southern and northern parts of Lake and St. Louis Counties. As an example, a precipitation pattern for Lake County is Two Harbors with 28.0 inches, Isabella 30.4 inches and Ely-Winton 26.5 inches. The respective mean summer temperatures are 58.3, 59.1, and 61.3. For St. Louis County, precipitation for Duluth is 30.3 inches, Hibbing 24.9 inches, Virginia 27.3 inches, and International Falls 24.7 inches. There are also substantial differences in total GDDs throughout the two counties.

This climate information is useful for analyzing the range of site indexes for selected species-soil combinations. It would also seem to be very meaningful for any land classification system used in Minnesota for the purpose of characterizing site quality.

A similar comparison of site index for selected tree species by stand types might result in information that would be helpful for gaining a better understanding of range in site index values. Such a comparison is beyond the scope of this summary, but certainly should be considered for future projects designed to refine site index information.

MINNESOTA COOPERATIVE SOIL SURVEY INFORMATION

The balance of this summary is based on site index information collected and prepared by members of the Minnesota Cooperative Soil Survey. There are 4,397 tree measurements and appropriate subsets supporting the information presented in this section. All measurements are age and height for site index. No destructive sampling took place; thus no attempt is made to infer volume or to establish temporal growth patterns. It should be noted that different species with the same site index will not necessarily have equal volumes per unit area at a specific age.

Tables are available for estimating volume from site index data for those readers who might be interested. Readers should also keep in mind that an unequal distribution of measurements for different species and soils somewhat limits the kinds of comparisons that can be made for the various species-soil combinations.

Table 5 is a summary of the MCSS statewide information. Tree measurements were collected from natural stands and some plantations. Most of the plantations are the results of Civilian Conservation Corp projects and are mainly jack pine *(Pinus banksana)*, red pine *(Pinus resinosa)*, white pine *(Pinus strobus)*, and white

Table 3. County-species-site index comparisons for selected species in Aitkin and St. Louis Counties.

County	Source	Species	Age mean	Site Index mean	max	min	Samples
Aitkin	J.Pine	CSA	37	62	80	39	101
		MCSS	55	68	81	53	24
		FIA	ID *	ID	ID	ID	ID
	R.Pine	CSA	48	61	80	23	173
		MCSS	55	70	93	50	103
		FIA	ND **	ND	ND	ND	ND
	B.Spruce	CSA	78	33	60	19	750
		MCSS	76	40	48	32	34
		FIA	71	36	65	26	9
	W.Spruce	CSA	32	61	78	45	22
		MCSS	53	69	86	47	90
		FIA	ID	ID	ID	ID	ID
	T.Aspen	CSA	45	70	95	35	3,359
		MCSS	48	82	102	57	321
		FIA	43	71	94	34	119
St. Louis	J.Pine	CSA	64	56	75	28	736
		MCSS	60	67	80	59	29
		FIA	52	60	80	40	27
	R.Pine	CSA	78	52	75	30	495
		MCSS	70	62	80	42	19
		FIA	65	54	75	42	15
	B.Spruce	CSA	82	35	65	23	2,390
		MCSS	80	43	46	38	9
		FIA	62	43	75	24	63
	T.Aspen	CSA	51	68	99	38	4,066
		MCSS	58	71	89	47	59
		FIA	41	67	99	36	428

* ID is insufficient data. ** ND is no data.

Table 4. Red pine site index-glacial outwash-climate values .

County	Annual Precipitation mean (inches)	GDDs * mean (annual)	Temperature Summer mean (May–Aug)	Site Index
Lake **	29.2	3,099	58.7	53
St. Louis ***	28.8	3,356	60.6	58
Clearwater	22.4	3,700	63.4	61
Aitkin	28.7	3,750	63.4	71
Houston	34.1	4,900	65.8	93

* GDD = growing degree days. ** All climate values are averages for Isabella plus Two Harbors. *** All climate values are averages for Duluth plus Virginia.

Table 5. Minnesota Cooperative Soil Survey statewide species-age-site index.

Species	Age mean	Age max	Age min	Site Index mean	Site Index max	Site Index min	N tree
White Ash	54	70	46	63	75	57	12
Black Ash	75	115	45	60	87	33	81
Bigtooth Aspen	53	85	24	68	114	45	245
Trembling Aspen	52	95	21	67	104	23	1,027
Balsam Fir	45	98	21	58	95	37	350
Basswood	59	79	43	70	86	58	88
Paper Birch	56	95	28	57	81	36	497
White Cedar	88	152	54	33	49	22	28
Sugar Maple	67	105	40	54	80	36	81
Red Oak	65	114	36	67	88	40	347
White Oak	72	104	36	55	76	44	21
Jack Pine	59	135	20	59	92	34	339
Red Pine	56	142	20	59	93	28	394
White Pine	67	124	28	52	98	28	209
Black Spruce	64	165	31	41	54	30	272
White Spruce	55	136	28	60	86	31	313
Tamarack	54	125	26	52	77	32	81
Black Walnut	38	50	29	75	91	52	12
Mean values	58	110	32	58	85	37	Total 4,397

spruce *(Pica glauca)*. Generally, site indexes for pine growing in plantations exceeds those for natural stands by five to ten feet. Both age and site index values range substantially for several of the species-soil combinations.

Interestingly, the highest mean site index value is for black walnut *(Juglans nigra)* which also has the highest market value. Note the mean age of 38 for black walnut. Second highest is basswood, which is often used as an indicator of high quality sites. Basswood measurements represent sandy to clayey soils, and locations of measurements range from north central to southeast Minnesota.

Bigtooth aspen *(Poplus grandidentata)* has the highest recorded site index, followed by trembling aspen and white pine. Trembling aspen has the greatest range between maximum and minimum values (81). White ash *(Fraxinus americana)* has the smallest maximum to minimum value range (18).

The oldest tree measured is a black spruce (165 years). Black spruce also has the greatest range of ages (165 to 31). White cedar has the oldest mean age value (88) and the youngest is black walnut (38).

The low mean site index values for black spruce, tamarack, and white cedar reflect the influence of stands growing in low fertility bogs. Those species grow more rapidly in upland sites.

Age may be an important factor for some species. A summary of information for red pine revealed that the majority of trees having a site index in excess of 75 were less than 45 years old. But red pine more than 65 years old have values less than 75 and often less than 65. That relationship is true even for red pine growing in very similar environments.

In two adjoining counties in northeastern Minnesota, for example, based on 92 tree measurements, the mean site index for red pine less than 45 years old is 80; for red pine 45 to 60 years old mean site index is 65; and for red pine older than 65 years mean site index is 62 or less. Twenty-seven red pine growing in Menahga series, a soil developed in outwash sand and gravel, show that trees under 45 years of age have a mean site index of 76 and those older have a site index of 63. Forest inventory representatives also state that they do not find the older high site index counterparts of the young rapidly growing red pine.

This age factor clearly demonstrates that site index for young trees for selected species should be used with caution for determining long term growth rates, soil series and growth relationships, or site quality. See table 6 for examples of age and site index comparisons.

Numerous studies for tree growth patterns report that the first ten to fifteen years of growth can be extremely variable because of genetic differences, events in the environment that affect growth, and impacts from human and animal activities. Several researchers recommend that site index should be based on measurements of age at 4.5 feet above ground level and height measured above 4.5 feet.

Table 7 displays a comparison of county, soil series, species, site index and age information. Typically, species growing in the same soil series

Table 6. Site index versus age comparisons statewide.

Species	r2	Site index mean	max	min	Age mean	max	min	samples
Spruce, black	0.054	41	54	30	64	165	31	56
Pine, jack	0.103	59	92	34	59	135	20	317
Aspen, trembling	0.178	67	104	23	52	95	21	505
Basswood	0.215	70	86	58	59	79	43	42
Oak, red	0.232	67	88	40	65	114	36	194
Aspen, bigtooth	0.278	68	114	45	53	85	24	108
Pine, red	0.526	59	93	28	56	142	20	262
Spruce, white	0.712	60	86	31	55	136	28	71

Table 7. Comparison of county-soil series-species-site index-age.

County	Series	Species	Site index mean	max	min	Age mean	max	min	N tree
Aitkin	Ahmeek	P.Birch	72	81	65	50	59	41	12
St. Louis	Ahmeek	P.Birch	64	78	53	52	61	43	28
Aitkin	Ahmeek	T.Aspen	80	91	70	47	53	38	18
St. Louis	Ahmeek	T.Aspen	64	79	56	71	68	75	5
Aitkin	Dusler	T.Aspen	86	91	82	45	58	37	10
StLouis	Dusler	T.Aspen	75	80	70	48	59	41	10
Aitkin	Cromwell	P.Birch	66	77	58	58	68	50	23
St. Louis	Cromwell	P.Birch	63	74	54	72	76	59	15
Houston	Lamoille	R.Oak	58	86	41	70	100	53	16
Winona	Lamoille	R.Oak	63	66	58	88	92	83	10
Aitkin	Menahga	R.Pine	64	81	52	71	88	39	27
Itasca	Menahga	R.Pine	62	70	51	50	62	38	31
St. Louis	Menahga	R.Pine	81	89	73	41	54	31	13
Aitkin	Omega	R.Pine	77	93	62	39	80	26	14
StLouis	Omega	R.Pine	65	66	64	70	72	68	15
Lake of the Woods	Hiwood	J.Pine	62	68	52	65	76	59	33
StLouis	Hiwood	J.Pine	67	72	63	56	69	38	18
Aitkin	Spooner	T.Aspen	79	84	75	53	56	50	12
St. Louis	Spooner	T.Aspen	72	87	63	53	57	47	20
Lake of the Woods	Menahga	J.Pine	57	63	51	48	50	45	9
Itasca	Menahga	J.Pine	67	72	57	45	72	33	18
Wadena	Menahga	J.Pine	57	74	49	50	69	37	43
Itasca	Nashwauk	T.Aspen	73	80	66	44	53	38	24
St. Louis	Nashwauk	T.Aspen	74	85	58	51	61	35	30

have a higher site index in Aitkin County than in St. Louis County. An exception is the red pine growing in Menahga, a dry sandy soil. Also note the mean age of the red pine measured in St. Louis County. The site index for trembling aspen growing in Spooner soil in Aitkin and St. Louis Counties is similar and is probably due to the same age class, and trees measured are located in similar environments. The same is probably true for trembling aspen and the Nashwauk series, a dry loamy soil, for the same counties.

Trembling aspen growing in Dusler series, a moist soil with a high silt plus clay content, has a mean site index value of 86 for Aitkin County and 75 for St. Louis County. The maximum value reported for St. Louis County is 80.

Paper birch has a mean site index value of 72 for the Ahmeek series in Aitkin County and 64 in St. Louis County. Ahmeek is a dry, coarse, loamy soil. The St. Louis County mean is about equal to the minimum value reported for Aitkin (64 vs 65). Trembling aspen growing in Ahmeek has a mean site index value of 80 for Aitkin and 64 for St. Louis County. The minimum for Aitkin exceeds the mean for St. Louis County by six units. The mean for Aitkin is slightly higher than the maximum reported for St. Louis County.

Paper birch growing in the Cromwell series, a sandy soil, has similar site index for both Aitkin and St. Louis Counties. Mean site index values are 66 and 63 respectively.

Red pine growing in the Menahga series in Aitkin, Itasca, and St. Louis Counties has mean site indexes of 64, 62, and 81 respectively. The range between maximum and minimum is substantial, with the largest range being in Aitkin and the smallest in Itasca. The highest value (81) occurs in St. Louis and the lowest (51) in Itasca.

In contrast, for red pine growing in the Omega series, a dry sandy soil, the highest mean site index value (77) is reported in Aitkin. The mean value for St. Louis County is 65. The range in site indexes is 31 units in Aitkin as compared to only two units in St. Louis County. There is also a substantial range in age. In Aitkin the total range is 54 years; for St. Louis it is four years.

Jack pine growing in the sandy Hiwood series soil has a mean site index in Lake of the Woods County of 62 as compared to 67 in St. Louis County. Lake of the Woods has a range of 16 units and St. Louis County has a range of nine. Maximum values are similar for both counties, but the minimum varies by eleven units. Both values are highest in St. Louis County. In comparison, jack pine growing in another sandy soil, Menahga, has mean site index values of: Aitkin 71, Lake of the Woods 57, Itasca 67, and Wadena 57. The greatest range (25) occurs in Wadena and the smallest (12) in Lake of the Woods.

In an attempt to discover what elements in the environment might affect tree height growth, the dependent variable site index is compared to mean annual precipitation, total growing degree days (base of 40° F), mean summer air temperature (May through August), soil series, and silt plus clay. Soil series included sandy, coarse loamy, fine loamy, and very fine representatives. The results are expressed in table 8 for trembling aspen, paper birch, and red pine.

Total annual precipitation r2 values range from 0.0004 for trembling aspen to 0.181 for red pine. Total growing degree days values vary from 0.196 for trembling aspen to 0.577 for red pine. Mean summer air temperature r2 values range from 0.26 for trembling aspen to 0.585 for paper birch. Soil series has a range from 0.002 for paper birch to 0.091 for trembling aspen. Silt plus clay r2 ranges from 0.09 for red pine to 0.126 for trembling aspen. Combined r2 for all variables ranges from 0.44 for trembling aspen to 0.885 for paper birch.

As might be expected, elements of environments that affect the botanical range of species are also significant in Minnesota, where there are both sharply contrasting forest types and a distinct change from forest into prairie. This information shows that in those contrasting environments, the physical element is spatially less significant than are other elements. Subsequently, if an accurately defined soil series occurs across the botanical range of a tree species, a substantial range in site index values should be anticipated.

However, if climate is held as constant as information will allow, then selected properties of the soil become more meaningful. The climate for the summary in table 9 has an annual precipitation of 29 inches, 3,356 growing degree days, and a mean summer temperature of 61° F.

Table 9 depicts a summary of soil properties commonly considered for fertility, root development, and growth. The table is intended for informational purposes, generating interest for further investigations, and not as finite soil-tree correlations. Soil-tree relationships may change significantly with contrasting changes in the climate.

Soil samples analyzed are not all from sites having site index information. But they are

Table 8. Environment element r2 values and site index.

Species	Precipitation mean annual	Growing Degree (40° F)	Temperature May-August	Soil	Silt+Clay percent
T. Aspen	r2 0.0004	0.196	0.26	0.091	0.126
		r2 0.213			
			r2 0.281		
				r2 0.345	
					r2 0.44
P. Birch	r2 0.0003	0.56	0.585	0.002	0.139
		r2 0.662			
			r2 0.708		
				r2 0.737	
					r2 0.885
R. Pine	r2 0.181	0.577	0.41	0.067	0.09
		r2 0.62			
			r2 0.64175		
				r2 0.64223	
					r2 0.689

representative of specific soils having site index data for three or more sites. Information used for this summary includes mean site indexes for selected species sorted by dry sandy, coarse loamy, fine loamy, and very fine texture classes with root zones free of physical barriers to root development and growth. There are a minimum of 15 measurements for each combination.

A combination of calcium in the upper 20 inches of soil and jack pine site index has the highest r2 (0.972). The lowest value (<0.001) occurs five times in the table, involving three species and four elements. Most of the ensuing discussion relates to the five soil elements with the highest values for each species.

For trembling aspen the most important soil element is potassium in the upper 20 inches of soil followed by phosphorus in the 20–40 inch layer, phosphorus in the upper 20 inches of soil, calcium in the upper 20 inches, and cation exchange capacity in the upper 20 inches. Four of the top five are directly related to elements in the upper 20 inches of soil. The lowest correlations are with calcium in the 20–40 inch depth and with available water capacity in the upper 20 inches. Both r2s are less than 0.001.

Table 9 Uniform climate and site index-species-forest soil relationships.

Soil element*	T. aspen	P. birch	R. pine	J. pine	W. spruce	B. fir	Sum
	Species and r2 Values						
caa	0.396/4**	0.239	0.922/3	0.972/1	0.131	0.314	2.974
cab	<0.001	0.098	0.687	0.612	0.449/3	0.055	1.901
mga	0.001	0.098	0.706	0.619	0.362	0.053	1.839
mgb	0.028	0.206	0.56	0.467	0.371/5	0.141	1.773
ka	0.661/1	0.408/5	0.037	0.005	0.046	0.342/5	1.499
kb	0.131	0.282	0.456	0.345	0.17	0.203	1.587
ceca	0.259/5	0.542/2	0.501	0.533	0.08	0.628/1	2.543
cecb	0.009	0.15	0.629	0.54	0.39/4	0.094	1.812
pa	0.418/3	0.502/3	0.71	0.768	<0.001	0.595/2	2.993
pb	0.454/2	0.241	0.893/4	0.956/2	0.182	0.312	3.038
oca	0.101	0.615/1	0.022	0.01	0.66/1	0.585/3	1.993
ocb	0.057	0.454/4	0.202	0.155	0.649/2	0.392/4	1.909
awca	<0.001	0.007	0.831	0.73	0.072	<0.001	1.640
awcb	0.045	0.004	0.961/1	0.902/4	0.154	0.024	2.090
uniform	0.1	0.004	0.948/2	0.918/3	0.321	0.021	2.312
si+c	0.002	0.006	0.872/5	0.781/5	0.126	<0.001	1.787

* The "a" and "b" represent respective depth classes of 1 to 20 inches and 21 to 40 inches. Thus, caa is calcium in 1 to 20 inches and cab is for 21 to 40 inches. Sum of r2 for a=15.48 and b=14.11.

ca=calcium, mg=magnesium, k=potassium, cec=cation exchange capacity, p=phosphorus, oc=organic carbon, awc=available water capacity, uniform=uniformity of soil particles in depth classes of less than 13 inches, 13 to 20 inches, 21 to 40 inches, and greater than 40 inches, si+c=percent silt plus clay.

** /# is ranking of r2 for top five values.

Thus, for trembling aspen in this climate and with soils varying from sandy to clayey and moist to dry, a special emphasis ought to be placed on characterizing or evaluating those four elements in the upper 20 inches of soil.

Paper birch site index is correlated most strongly with organic carbon in the upper 20 inches of soil. The next four significant elements are cation exchange capacity, phosphorus, potassium in the surface 20 inches, and organic carbon in the 20–40 inch portion of the root zone. The lowest correlation (0.004) is associated with available water capacity between 20 and 40 inches of depth, and with uniformity of materials at a 40 inch depth. Four of the top five values are soil elements in the upper 20 inches of the root zone.

Red pine site index correlated strongly with uniformity of physical soil properties and the amount of calcium in the upper 20 inch portion of the root zone and with available water capacity, amount of phosphorus, and silt plus clay level in the 20–40 inch portion.

Jack pine site index correlated strongly with calcium in the upper 20 inches of the root zone, and with phosphorus, uniformity of soil texture and available water capacity in the 20–40 inch portion of the root zone. The lowest value is (0.005) for potassium in the upper 20 inches.

White spruce site index is correlated closely to organic carbon throughout the root zone. It is also correlated with calcium, cation exchange capacity, and magnesium in the 20–40 inch portion of the root zone. The lowest value (<0.001) is for phosphorus in the 20–40 inch portion of the root zone.

Balsam fir is correlated closely to cation exchange capacity, phosphorus, potassium and organic carbon in the upper 20 inches of the root zone. The lowest values (<0.001) are for available water capacity in the upper 20 inches and silt plus clay.

A comparison for all species and all soil properties per sum of r2 values is red pine > jack pine > white spruce > paper birch > balsam fir > trembling aspen. Red and jack pine have the same soil properties in the top five r square values, but the ranking differs. The same is true for paper birch and balsam fir. Trembling aspen and paper birch overlap somewhat as do white spruce and balsam fir. White spruce is most different from the other five species.

Based on this summary, there is no single site indicator species. Some species could be paired, such as red and jack pine, and paper birch and balsam fir. A strong correlation of balsam fir site index with soil properties in the upper 20 inches of soil may explain part of its high mortality during and following droughts. Red pine, with its reported narrow genetic nature, is a reasonable candidate for comparing soil properties.

Soil elements with the sum of highest r squares are pb > pa > caa > ceca > uniformity of soil texture. Phosphorus in the total 40 inch depth ranked in the top five r2 values for five of the six species. It ranked second for three of the species and third for two species. Organic carbon in the upper 20 inches ranked number one for both paper birch and white spruce. Potassium in the upper 20 inches has the lowest r2 sum, even though it ranked first for trembling aspen. Based on the sum of the r squared values, the soil elements in the upper 20 inches are slightly more significant than those in the lower 20 inches. The difference is ten percent.

IV. CONCLUSIONS

The variety of natural resource inventories common in Minnesota provide a large amount of information that is useful for estimating the productive capacity of the land for different tree species. Growth information produced by the different forest inventories can be combined with reported climate and physical resource information to provide a better estimate of the productivity of the various environments that prevail in Minnesota.

This information also has some use for evaluating current and potential productivity for selected tree species in the contrasting environments.

The information also depicts the wide range of the commonly used site index for a given species growing in like or unlike environments. With a current goal in the State to more than double tree yields by 2015, (Report prepared by the Governor's Blue Ribbon Commission on Forestry and Forest Products; 1989; page 17) this information may be useful as part of a beginning point for increasing yields.

Annual precipitation, total growing degree days (base 40° F), and mean summer temperatures are important for statewide analysis of site index information. The comprehensive climate information available in Minnesota is a very important factor for explaining a portion of the different rates of growth for a given species having like physical properties in the root zone. This information ought to be a basic part of the design and implementation of biological and physical resource inventories in the forests of Minnesota.

Soil information becomes increasing useful as other elements of the environment are characterized. Findings reported here agree with past conclusions (Carmean 1975 and Grigal 1984) that soil series do not correlate well with tree growth. However, selected analyses of soil elements in the root zone within a uniform environment correlate well with tree site index. The correlation varies with individual elements and species. These correlations are important for preparing and carrying out prescriptive management and for maintaining productivity.

A large number of samples did not significantly change the mean site index values for species groups or individual species. Site indexes for most species were higher in the Minnesota Cooperative Soil Survey data set than either the Cooperative Stand Assessment or Forest Inventory and Analysis sets. Values in the latter two sets were similar. One reason for the higher values in the MCSS data was an attempt by the staff to identify "potential productivity" in contrast to CSA and FIA that reported the entire wide range of timber stand conditions.

Perhaps more or equally important as total number of samples is a clearly defined objective which supports the human resource investment. That objective coupled with concise direction and guidelines for selecting sites, selecting individual trees, and making precise and accurate measurements, comprise what may qualify as the top priority items for developing an efficient and high quality data set for site index.

Minnesota's diverse environments are very useful for testing the effect of climate and soil elements in the root zone on site index. Statewide annual precipitation, total growing degree days, and mean summer temperature are important to tree growth. They should be combined with local soil conditions for estimating site quality. Holding climate somewhat uniform for comparisons increased substantially the importance of certain soil elements in the root zone. That demonstrates the potential usefulness of combining climate and soil elements for use in land classification systems.

Age seems to affect site index for certain species. White spruce is influenced the most and black spruce the least. Site index summaries ought to reflect this influence since it may account for part of the range in those indexes. In areas of Minnesota where strong winds and ice storms are common, a special effort would seem to be in order for evaluating their effect on age and height growth relationships and ultimately on site index.

Minnesota forests may have the potential for sizable increases in productivity as indicated by the summary of site index and environment information in this report. This statement is made with the knowledge that site index and yield are not always directly correlated. But the range in site index for a given species growing in a uniform environment certainly suggests that perhaps past impacts on trees from which age and height data were collected may have in fact depressed growth rates. Subsequently, there may be valid opportunities for increasing growth rates with routine forest management and silviculture practices. A screening of sites in specific environments for application of silvicultural and management strategies could begin with some of the information presented in this report.

An indicator species for predicting the site index of other species would be difficult to identify with the background information used in this report. Because there are unanswered questions about the causes for the wide range of site indexes for a given species, the relationships between species would be questionable. A pairing of selected species for identifying significant elements in the root zone may be possible, as indicated in table 9.

Examples of potential pairing are jack pine with red pine and paper birch with balsam fir. Such pairings would not necessarily produce equal site indexes but would indicate elements in the root zone of similar importance to growth for the paired species.

An indirect estimate of site index for six species cited in table 9 is possible using climate and the soil elements listed in the table. The most reliable estimate would be for red and jack pine. Estimates for white spruce, paper birch, and balsam fir would be less reliable, and estimating the site index for trembling aspen would be risky. Information for cultural activities and genetic variation in combination with climate and soil elements may improve the accuracy of estimating site index for a species growing in a uniform environment.

Balsam fir and paper birch appear to be sensitive to soil elements in the upper 20 inches of the root zone. Thus, disturbances in that part of the root zone should be given special consideration for prescriptions featuring those two species. White spruce, jack pine, and red pine tend to respond to soil elements deeper in the root zone.

It is clear from the data summarized for this report that identifying "what makes a tree grow" still offers great challenges to natural resource staffs. Questions like "What is the limiting factor for tree growth in a specific environment?" or "Does a single limiting growth factor control a species in all environments?" have been asked and studied in the past. The answers are still incomplete and offer resource staffs a complex challenge.

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