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A Review of Literature Relating to Quaking Aspen (Populus Tremuloides) Sites

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RELATING TO

QUAKING ASPEN SITES

by

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A REVIEW OF THE ASPEN SITE LITERATURE RELATED TO QUAKING ASPEN IN MINNESOTA

by

M. L. Heinselman and Z. A. Zasada[2]

INTRODUCTION

Minnesota foresters and forest owners have long felt a need for more complete information on the capacity of various areas for the production of aspen products. The aspen type occupies an estimated 5,997,000 acres in the state, or one-third of the total commercial forest area. It is the largest single cover type. Quaking aspen (Populus tremuloides Michx.), the most common tree in this type, grows on a wide variety of soils throughout all of the forested area of northern Minnesota, but in many areas yields are poor, and in some instances no salable products are produced at all. On the other hand, in the better aspen areas this tree attains large diameters and yields 35 or more cords per acre in 40 to 60 years. Markets for aspen have been expanding rapidly. In recent years it has become the leading pulpwood species in the Lake States. Large volumes are also used for sawbolts, matchbolts, and other products.

Modern forest practices require better methods of evaluating the growth potential of aspen lands. The quality of aspen stands 30 years old or more can be judged fairly well by such measurable stand characteristics as age, diameter, total height relationships, stocking, and evidence of disease. But landowners often need to know whether younger stands can be counted on to produce a crop of pulpwood or sawtimber. Decisions on the need for conversion plantings, stand improvement work, planning of future cuts, the value of the land for purchase or sale, and similar questions may hinge on the area's productivity for aspen. Increased basic knowledge about the factors affecting aspen growth also is needed to place management recommendations on a sounder basis.

1/Maintained at St. Paul 1, Minnesota, by the U. S. Department of Agriculture, Forest Service, in cooperation with the University of Minnesota.

2/Research Foresters, Headwaters Forest Research Center, Lake States Forest Experiment Station, Grand Rapids, Minnesota.

Past work on the productivity of land for various tree species has shown that growth usually is influenced by a wide variety of factors such as chemical composition of soils, available soil moisture, climate, plant and animal competition, and stand history. The word "site" is the accepted technical term now used in referring to the entire complex of factors which determine tree growth.

A great deal of research has already been done on forest sites. Some dealt specifically with aspen sites, and some applies indirectly to aspen either by inference, or because the approach or techniques may be applicable. Familiarity with previous work is essential as a starting point for current research. This report presents a review of the applicable literature and summarizes available data regarding Minnesota's aspen sites. It will be confined to a consideration of quaking aspen. The bigtooth aspen (*Populus grandidentata* Michx.) will not be covered because it is of lesser importance in Minnesota, and relatively little research data is available on it.

Each particular investigator has tended to concentrate on those factors concerning forest sites which he felt to be most critical for the species being studied. For purposes of organization the literature will be discussed under the following topics:

1. Growth and yield.
2. Soils.
3. Moisture relations.
4. Climate.
5. Fire.
6. Diseases and insects.
7. The "Total Site" approach.
8. Plant indicators.

GROWTH AND YIELD

The earliest detailed study of growth and yield of quaking aspen in the Lake States was reported by Kittredge and Gevorkiantz in 1929 (44). They analyzed the possibilities of aspen as a forest crop, and prepared a set of yield tables for five site classes. Four tables were constructed showing yields in cubic feet, board feet International, board feet Scribner Decimal C, and peeled cords. Site index was based on total height of dominants at 50 years. Site index curves are presented and yields are given for classes 80, 70, 60, 50, and 40 feet. Predicted yields per acre range from 80 cords at 80 years for site index 80 to only 5 cords at 50 years for site index 40 (table 1).

These yield tables were based on well-stocked stands, and their authors warn against the errors that will result if they are used without adjustment for predicting yields from understocked stands. They estimate that two-thirds of the aspen-birch area was understocked in 1929.

Table 1.--Cordwood yields for well-stocked aspen in trees 4 inches and more in diameter at breast height; after Kittredge and Gevorkiantz, (44)

Site index at 50 years	Age	Average total height of dominants	Peeled volume per acre to 3-inch top
Feet	Years	Feet	Cords
80	30	59	32
	50	80	63
	70	93	76
	80	98	80
70	30	51	25
	50	70	55
	70	82	67
60	30	44	12
	50	60	44
	60	66	51
50	40	44	11
	50	50	26
40	50	40	5

Rotation ages for the various sites are discussed, and it is concluded that 50 years represents the culmination of average annual cubic-foot growth and would thus be the rotation age for site indexes 60, 70, and 80. In site index classes 40 and 50 the stands do not attain an average diameter of 6 inches (considered the minimum operable size at that time) until beyond age 50. Rotations would, therefore, have to be 60 years for index class 50. "It is doubtful whether aspen stands will survive long enough to become marketable" on the poorest sites, they conclude. Production of sawtimber would usually require a rotation of 60 or 70 years, a practice that they advise only for index classes 80, 70, and the upper part of 60. Stands as old as 95 years, averaging 100 feet in height, with trees up to 18 inches in diameter, were encountered in the survey, but "after 60 years the average growth declines owing to the death of the crowded trees."

Johnson, Kittredge, and Schmitz (41) discussed aspen yields in 1930. Condensed versions of the yield tables published by Kittredge and Gevorkiantz (44) were reproduced in this work. They note that:

> ... aspen grows rapidly; in fact it is one of the most rapid growing species in the Lake States. The rate of growth varies, however, with the soil and site conditions, and with the age of the stand. For example, on a medium site at 30 years, well stocked stands grow at the rate of about 4/10 of a cord per acre annually, and at 50 years almost 9/10 of a cord, after which the average annual growth rate diminishes. On a good site at 50 years, the growth rate may be as much as 1-1/4 cords per acre annually, and on a poor site as little as 1/10 of a cord.

They observe that, in practice, growth and yields are much less than those predicted by the tables due to stand openings and understocking. Sample cruises made it "evident that aspen stands over large areas have less than half the yields indicated by the tables." They stress the need for more information on the ages at which aspen deteriorates, especially on the poorer sites where it may die before reaching merchantable sizes.

The yield tables and site index curves from the original work of Kittredge and Gevorkiantz were again published in 1934 by Brown and Gevorkiantz (16) in a compendium of volume and yield tables that has been widely used since then.

In 1936 Robert T. Anderson (5) reported the experience of the Forest Survey with aspen yields. Survey figures showed that typical volumes in natural aspen stands fell far below the yields predicted by the yield tables. Reasons given for low yields were: understocking, poorer form, high defect, and different utilization standards. He prepared a set of "discounted" yield tables which show volumes for three site classes reduced to Survey utilization standards and for typical cull percentages. These tables are closer to actual yields from well-stocked stands, he believes. Volumes run from 52 cords at 80 years on good sites, to 31 cords at 60 years on poor sites.

In 1940, yield tables were published by the Lake States Station for three site classes based on average volumes in undisturbed stands, adjusted for Survey standards and defect (6). They were based on volumes over larger areas than "normal" yield tables and thus show smaller yields. Typical volumes from these tables are 48 cords at 80 years for good sites, and 25 cords at 50 years or 34 cords at 80 years for poor sites.

The first estimate of Minnesota's aspen areas by site classes was published by Cunningham in 1946 (23) based on Forest Survey plot data. Some 1,500,000 acres were estimated to be on good sites, 4,125,000 acres on medium sites, and 1,875,000 acres on poor sites.

Zehngraff (91) in 1947 summarized much of the previous work on growth and yield. He states that in pure stands on good sites the best trees will attain heights of 80 feet and diameters of 15 inches at 60 years. "On average sites the rotation of necessity must be less (about 50 to 55 years), at which time dominant trees reach a height of about 65 feet and a diameter of about 12 inches." In discussing yields by sites, he points out that "earlier estimates of volume yields were too high, chiefly because proper weight was not given to: (a) the exceptionally high natural mortality rate of the species; (b) the high cull percentage, especially in older stands; and (c) the natural slowdown in growth with age." A revised yield table prepared by Gevorkiantz for the Forest Survey was published in this report (table 2).

In a Journal of Forestry article in 1949, Zehngraff (92) sums up yields of aspen on various sites as follows:

> Despite the fact that aspen springs up on all kinds of soils, it is one of the most sensitive species in site requirements. On favorable sites aspen develops into a good tree; on unsuitable sites it is short and scrubby and breaks down at an early age... Only the good sites will produce high quality sawlogs and veneer. The medium sites will yield low-grade sawlogs and box bolts, but the main product on these sites will be pulpwood. Some of the poor sites will produce small pulpwood, but most of them are "off site" areas; that is, they will not yield merchantable products under present utilization standards.

Zasada (90) has analyzed the relation of yields and rotations to sites (also published by Zehngraff (91)) as follows:

<u>Good sites</u> -- aspen reaches sawlog size at the rotation age of about 55 years. Yields of 9,100 board feet or 46 cords per acre and higher, are attainable.

<u>Medium sites</u> -- the trees produce small logs and pulpwood at the rotation age of about 45 years. Estimated maximum yields are about 6,000 board feet or 33 cords per acre.

<u>Poor sites</u> -- aspen seldom reaches more than pulpwood size at the rotation age of about 30 years. Maximum yields may run up to 18 cords per acre, but more often they are substantially less ... much of the poor site aspen is noncommercial at the present time.

Table 2.--Yield of aspen by age and site classes, gross volumes per acre; (Gevorkiantz) from Zehngraff (91)

Age class	Site classes					
	Good	Medium	Poor	Good	Medium	Poor
	Standard cords[1]			Board feet - Scribner[2]		
20	8	..	..	..	..	..
25	19	7	..	..	..	..
30	29	16	5	1,300	300	..
35	36	24	13	4,000	1,400	..
40	42	30	17	7,000	3,000	1,100
45	46	32	18	8,500	5,000	2,400
50	47	33	16	9,000	6,000	3,000
55	46	30	13	9,100	6,000	2,900
60	43	26	10	9,000	5,800	2,500
65	37	20	6	8,400	5,200	1,800
70	29	14	4	7,400	4,500	1,400
75	21	9	..	6,000	3,200	700
80	12	4	..	4,200	1,500	..

1/ Cords: Gross volume in standard cords of peeled wood in trees 4 inches d.b.h. and larger, to a minimum diameter of 3 inches inside bark.

2/ Board foot volumes are gross volumes, by the Scribner rule, of trees 7 inches d.b.h. and larger, to a minimum diameter of 6 inches inside bark.

SOILS

Surface Geology and Soil Survey Work

Work on soil-site relationships requires background information on the surface geology and general characteristics of the soils in the area. Although our knowledge of these subjects relating to Minnesota is still rapidly expanding, a good deal of useful published material is already available.

Between 1915 and 1918, three publications on the surface geology of Minnesota by Leverett (47), and Leverett and Sardeson (48, 49), were issued by the Minnesota Geological Survey. Additional work by Leverett and Sardeson was published in 1932 (50). Large-scale and quite detailed maps are included showing the glacial deposits on which the forest soils of northern Minnesota have developed. The principal features shown are till plains by texture classes, moraines, eskers, outwash plains, old lake beds, old beach lines, rock outcrops, the boundaries of various glacial drifts, and some contour lines. They provide a good basis for understanding present topography and soils relations.

The soils of northern Minnesota are formed from three glacial drifts, according to Leverett and Sardeson. The Middle Wisconsin or Cary ice invasion originating in the Hudson Bay area moved into the state from the northeast. It brought in a reddish drift that is coarse-textured and generally low in lime. Two other ice fronts are believed to have entered the state later during the Late Wisconsin or Mankato ice invasion. The major ice movement in this period was the so-called Keewatin ice sheet which moved in from the northwest, depositing a heavy-textured, gray-colored drift with a high lime content, carried down from a center in northern Manitoba. The other front in this invasion moved into Minnesota from the Lake Superior basin and is known as the "Superior Lobe." Superior Lobe drift is red in color, variable in texture, but generally finer than the Cary red drift, and contains some lime. According to Leverett and Sardeson, the Minnesota portion of the bed of glacial Lake Agassiz occupied not only the Red River basin but also a considerable portion of northwestern Minnesota including the "Big Bog" region.

Some of the drift boundaries as interpreted by Leverett and Sardeson have recently been questioned by Sharp (71) and Wright (88). The major question seems to concern the limits of the Superior Lobe and its dating. Surface soils are quite diverse in origin in southern St. Louis County, and in Carlton, Pine, Aitkin, and possibly in Crow Wing Counties. The Superior Lobe deposit is generally thin, and in places did not cover the Cary red drift. From the forest soils standpoint, however, there seems to be fairly general agreement on the nature of the surface drift over most of northern Minnesota.

From the standpoint of aspen site research, this information on surface glaciation is important, because soil textures, soil nutrients, rock outcrop, soil drainage, and other soil features are determined to a considerable degree by the nature of the glacial deposits.

A program of soil surveys has been under way in Minnesota for many years, sponsored by the Bureau of Chemistry and Soils of the Department of Agriculture, and the Agricultural Experiment Station of the University of Minnesota. This program has been concerned mainly with agricultural land and, therefore, has moved rather slowly in the north. Survey reports including detailed soil maps have now been published for the following forest area counties: Pine (73), Kanabec (60), Mille Lacs (15), Lake of the Woods (10), Wadena (25), Hubbard (59), and the "prairie fringe" area of the Red River Valley Counties (61). These reports with their accompanying maps and soils descriptions supply much useful data on soil properties for these areas, but the most important aspen-producing regions have not yet been covered. A very generalized coverage of the unsurveyed portions of the aspen area is available, however, in a bulletin by McMiller (58) published in 1947.

Some areas in Pine, Carlton, and St. Louis Counties are similar enough to adjacent portions of Wisconsin so that data from Wilde, Wilson, and White (85) can be applied by inference. The state of fertility factors in three texture classes is shown in profile analyses reported by these authors from nearby Wisconsin counties (table 3). While the productivity of these soils for aspen was not reported, very similar soils in Minnesota support a considerable acreage of aspen.

Early soils work by Marbut (55) and others placed most of the soils in Minnesota's aspen region in the Podzol group. This great soil group was visualized as being roughly coextensive with the conifer forests of northern and northeastern Minnesota. To the south and west of this region a belt of Brown Forest soils or Gray-Brown Forest soils was recognized in the regions where deciduous trees were more prominent. Still further south and west the Prairie soils and Chernozems occupied the true prairies.

In recent years soils men have recognized that the soils derived from Late Wisconsin gray drift in northern Minnesota possessed several characteristics that did not agree with the usual concept of a Podzol. Nygard, McMiller, and Hole (62) report that such soils, because of the highly calcareous gray till which makes up the parent material, are now placed in a separate great soil group termed the Gray Wooded soils. In spite of strong leaching under predominantly coniferous cover types, these soils "show only slight acidity to mild alkalinity, and a high base status." Duller color in the B horizon, more blocky structure, less cementation, and other profile features, also distinguish these soils from the Podzols. Also, in the report mentioned above, some of the Cary red drift and Superior Lobe soils of northeastern Minnesota were assigned to the Brown Forest soils rather than the Podzols. True Podzols and Brown Podzolic soils are also recognized on the red drifts. A narrow belt of Degraded Chernozems occupies the prairie-forest transition area in the eastern Red River Valley. Profile analyses of representative soils of each group were published by Nygard, McMiller, and Hole (62), and are reproduced here because they are frequently aspen sites in Minnesota (table 4).

Table 3.--State of fertility factors in three profiles from northwestern Wisconsin; after Wilde, Wilson, and White (85)

Soil description	Location (county)	Native vegetation	Horizon	Depth	Reaction	Total N	Base exch. 1/ capacity	Exch. Ca	Exch. Mg	Avail. K_2O	Avail. P_2O_5
				Inches	pH	Pct.	M.e./100g.	M.e./100g.	M.e./100g.	Lbs./acre	Lbs./acre
Melanized fluvio-glacial sand	Douglas	Jack pine, red pine	Surface layers	0-7	5.5	0.28	8.9	6.2	1.1	200	69.2
Melanized gley loam	Washburn	Hardwoods	Surface layers	0-7	5.7	.49	24.7	15.7	3.0	620	81.5
										P.p.m.	P.p.m.
Podzolized lacustrine clay	Ashland	White pine, hardwoods, spruce-fir	A_0	0-3	5.6	1.23	73.7	38.4	10.3	472	66.0
			A_2	3-18	4.3	.02	9.2	3.2	1.2	27	7.5
			B	18-40	4.6	.04	14.9	4.7	1.3	48	55.2
			C	40+	7.3	Tr.	19.2	14.3	3.7	65	23.0

1/ M.e./100 g. = mil-equivalents per 100 grams.

Table 4.--Profile characteristics of four great soil groups; after Nygard, McMiller and Hole (62)

Great soil group	Soil type	Location of sample	Horizon	Reaction	Base saturation	Clay	Organic carbon	Exch. Ca	Exch. Mg
				pH	Pct.	Pct.	Pct.	M.e./100 g.	M.e./100 g.
Gray Wooded	Nebish silt loam	Ottertail County, Minn.	A_2	7.4	88	9.0	0.47	6.2	1.4
			B_{21}	7.1	87	29.2	0.38	13.8	3.6
			B_{22}	7.0	88	29.5	0.30	13.5	4.2
			C	7.8	100	8.8	0.14	17.4	2.0
Brown Forest	Ahmeek silt loam	Lake County, Minn.	A_1	5.2	40	17.0	8.53	13.4	2.0
			B_{21}	5.1	26	16.9	3.65	5.3	1.6
			B_{22}	5.1	26	14.8	1.58	4.2	1.3
			B_3	5.5	35	10.5	0.77	3.9	2.4
			C_1	6.2	78	11.2	0.15	8.7	4.6
			C_2	6.3	82	11.2	0.16	9.4	4.9
Brown Podzolic	Omega loamy sand	Douglas County, Wis.	A_1	4.7	29	3.1	4.44	4.9	0.9
			B_{21}	5.4	22	4.4	0.95	1.0	0.3
			B_{22}	5.3	30	4.3	0.12	0.6	0.2
			C_1	5.8	9	1.8	0.07	0.1	0.1
Degraded Chernozem	Waukon loam	Ottertail County, Minn.	A_1	7.1	88	21.3	5.17	19.0	10.0
			A_2	7.0	86	18.5	2.16	15.6	3.6
			B_{21}	6.0	78	29.2	0.34	12.4	4.3
			B_{22}	7.0	92	30.6	0.45	19.1	9.7
			C	8.0	100	20.9	0.14	19.1	6.9

Additional laboratory analyses of common Minnesota aspen soils were published by the Beltsville laboratory of the U. S. Department of Agriculture in 1952 (7). Six of these analyses have been placed in the appendix to facilitate comparison with other soils data (tables 19-24).

The Relation of Soil Characteristics to Site Quality

One of the earliest opinions on the soil requirements of quaking aspen was expressed by Baker in 1925 (9). He states that:

> ... aspen grows (in the Central Rockies) in practically every variety of soil found in the climatic belt to which it is suited, from loamy sands ... to heavy clays ... but the development of stands varies considerably on different soils. The chief direct influencing factor is rockiness of the soil, which by hindering the lateral spread of the shallow roots, and interfering with the tendency to rise close to the surface, restricts the reproductive ability of the tree and its development ... The best aspen development is on rich, deep-soiled flats supplied with plentiful moisture.

In 1929 Kittredge and Gevorkiantz (44) reported on soil-site relationships in the Lake States as follows:

> ... the medium to coarse sandy soils of outwash plains or sandy moraines, which are drouthy and low in nutrients, usually have site indexes below 55, except where the soil is close to swamp or ground water level. The fine sandy soils of outwash plains, the clay and clay loam soils around the shores of Lake Superior, and the shallow sandy loam soils on the rock outcrops in northeastern Minnesota belong also to site index classes less than 55. The site index classes above 67 include the silt loam soils on boulder clay or clayey moraine or on the heavier soils of old lake beds and those not too shallowly underlain by rock; and fine sandy soils on boulder clay. The other group of soils on which aspen was found are in the intermediate site classes between 55 and 67 ... Certain large areas with predominantly good and poor sites for aspen may be mentioned. Poor sites ... are characteristic of the hilly, gravelly moraines that occupy a large area in Vilas and Oneida Counties in ... Wisconsin, and a strip of similar topography from Aitkin through Cloquet and northeastward into Lake County in Minnesota ... The areas of loam and silt loam soils of northwestern Itasca County and of Beltrami County southeast of Red Lake ... are excellent sites ...

Westveld (81) reported on a study of soil-site factors for Michigan northern hardwoods in 1933. The best sites for this cover type were found to occur on loams and sandy loams with a sandy clay till or drift substratum at 25 to 30 inches, or on silt loams and loams with either clayey subsoils or open coarse sand, gravel, or cobbles below 40 inches. The poorest sites were shallow sandy loams resting on bedrock. Loamy sands, sandy loams, and loams with yellow sand below 15 to 30 inches were intermediate in productivity. Apparently moderately heavy-textured soils with deep profiles and a good soil moisture supply are factors promoting the best northern hardwood production.

Roe (66) and (67) reports a detailed survey of the relation of forest types to soil types in the Lake States. On some 500 plots, site index, soil texture, color, and topography were recorded, as well as vegetation and plot history data. The relationships of aspen site index to soil types and also to profile characteristics were analyzed. Essentially his data show that the sandy, rocky, or excessively drained soils are poor aspen sites, while the best sites tend to be on loams with a heavy subsoil and moderately high water table. These relationships are best summarized in table form (table 5).

Table 5.--Relation of aspen site quality to soil groups in Minnesota, Wisconsin, and Michigan; after Roe (67)

Soil moisture relationships	Texture of surface soils	Character of subsoil		
		Rock	Sandy	Clayey
		(Average site quality)		
Dry	Sands	--	Poor	Poor
Fresh	Light loams and loamy sands	Poor	Poor	Medium
Moist	Loams and heavy loams	Medium	Medium	Good
Intermittently wet	Variable	Poor	Poor	Medium
Wet	Mucky	--	Medium	--

Roe found that aspen "occurs to a great extent on all soil groups and is not characteristic of any of them," although its growth rate varies widely from one soil to another. Some of the more common soil types in Minnesota are rated as to their average site quality for aspen (table 6).

Table 6.--Relation of site quality classes of aspen to soil types in Minnesota; after Roe (67)

Poor sites (Site index below 65.3)	Medium sites (Site index 65.3-70.1)	Good sites (Site index above 70.1)
Cloquet bouldery sandy loam	Nebish loamy fine sand	Dora Lake fine sandy loam
Hibbing loam	Sebeka loamy sand	Freer silt loam
Milaca very fine sandy loam	Taylor silt loam	Hibbing very fine sandy loam
Ontonagon clay		Nebish loam
Rockwood sandy loam		Ontonagon fine sandy loam
		Ontonagon silt loam
		Taylor clay loam

Another study of soil profile characteristics in relation to aspen site index was published by Kittredge in 1938 (45). Altogether, 277 field plots from Minnesota and northwestern Wisconsin were analyzed for one or more relationships. Soils data included thickness of litter and humus, texture, color, thickness of each horizon to 3 feet, topography, slope, aspect, and surface geological formation as mapped by Leverett and Sardeson. Field or laboratory soil-testing techniques were not used. Kittredge applied statistical analyses, and stratified his data in a number of ways to obtain the best correlation ratios between aspen site index and soils characteristics. The results of this analysis were as follows:

Soil characteristic	Correlation ratio[3/]
Soil class or texture groups	0.573
Geological formation groups	0.640
Combined texture and geological formation groups	0.699
Soil profile groups	0.795

3/ A correlation ratio of 0.00 indicates no relationship between the variables tested, while a ratio of 1.00 would indicate complete agreement.

These correlations are sufficiently high to indicate a definite relationship between site index and the soils groupings used. They are not high enough, however, to permit reliable prediction of site index from these factors alone. The mean site indexes for aspen for each of Kittredge's soil groupings are presented in tables 7, 8, 9, and 10.

The data from Kittredge's analyses indicate that the gray drift soils of Minnesota are frequently better aspen sites than the red drift soils. This may be partially a matter of textural differences, but within the same texture classes the gray drift soils still rank quite consistently better. Further work is needed to explain these findings. Nutritional factors, climatic differences between the soil regions, or other variables may be responsible. Kittredge did not have the benefit of later geological findings on the Superior Lobe drifts. If the soils of these drifts had been analyzed separately it is difficult to say just what effect they might have had on his results.

Roe's (66) and (67) data are in agreement with those of Kittredge on the significance of soil texture and moisture-retaining factors. Both investigations indicate that the heavier-textured soils with more available soil moisture tend to be good sites, while the dry, sandy or rocky soils are usually poor sites.

The 277 plots in Kittredge's study represent 54 different soil types. A chart showing the distribution of plots by site index on each soil type indicates that, within rather broad limits, soil types can be used as indicators of aspen site quality. The approximate site quality of several common Minnesota soils, based on this chart, is shown in table 11.

Comparison of Kittredge's data on soil types (table 11) with Roe's (table 6) indicates substantial agreement except for several soils. Kittredge's chart indicates that a range of at least two, and frequently three, site index classes may be found on the same soil type.

Barth (11) sums up the soil requirements of European aspen (*Populus tremula* L.) in Norway as follows:

> Aspen demands a light, loose, organic, and preferably lime containing soil of a fresh and moist nature, as characterized by the grass and herb-rich forest type. On dry, poor soil aspen does not develop well ... on such soils it usually also suffers heavily from center-rot, even in its youth. Nor does aspen like hard, heavy, or clay soils. It resents poorly drained soils as much as other tree species. On the other hand, it thrives well on wet soils where the ground water is in steady motion.

Table 7.--Relation between soil texture classes and mean site index of aspen; after Kittredge (45)

Soil class and drift	Plots	Mean site index
	Number	
Sand, red drift	15	52.7
Loam, red drift	11	56.9
Clay loam, red drift	12	57.2
Sand, gray drift	7	59.1
Sandy loam:		
Red drift	34	59.8
Gray drift	15	60.9
Peat	4	61.0
Fine sandy loam, red drift	23	61.8
Clay loam, gray drift	9	62.1
Fine sand, red drift	11	63.6
Silt loam, red drift	13	64.8
Loam, gray drift	2	66.0
Fine sand, gray drift	13	66.5
Fine sandy loam, gray drift	32	67.1
Silt loam, gray drift	26	68.6

Table 8.--Relation between surface formations and mean site index of aspen; after Kittredge (45)

Surface formation and drift	Plots	Mean site index
	Number	
Outwash, red and gray drift	12	51.2
Rock, red and gray drift	27	55.2
Lake-bed clay, red drift	12	57.6
Lake-washed sandy till, red and gray drift	6	59.0
Peat, red and gray drift	4	61.0
Sandy moraine:		
Red drift	39	61.3
Gray drift	31	63.7
Till, red drift	23	64.3
Lake-washed clayey till:		
Gray drift	16	64.8
Red drift	6	67.0
Clayey moraine, red and gray drift	16	67.7
Till, gray drift	37	68.8

Table 9.--Relation between combined texture-surface formation groups and mean site index of aspen; after Kittredge (45)

Soil group	Plots	Mean site index
	Number	
Sands and fine sands on red drift outwash	7	48.7
Sandy loam and heavier on red drift outwash	4	53.7
Clay loam on lake-bed clay	9	54.9
Red-drift fine sandy loam and silt loam on rock	8	55.1
Red-drift fine sand, sandy loam, and loam on rock	19	55.3
Sands on sandy moraine and on lake-washed sandy till	13	55.3
Peat	4	61.0
Red-drift fine sand and sandy loam on sandy moraine or lake-washed sandy till	23	61.4
Clay loam on lake-washed clayey till	12	62.6
Sandy loam on gray drift; sandy loam and heavier on sandy moraine or lake-washed sandy till	39	64.6
Sand and fine sand on gray drift; sandy loam, and fine sandy loam on red drift, on till, clayey moraine, or lake-washed clayey till	34	64.9
Sandy loam and fine sandy loam on gray drift; and heavier red-drift soils on till, clayey moraine, or lake-washed till	58	68.5

Table 10.--Relation between 22 soil-profile groups and site index; after Kittredge (45)

Soil-profile group	Plots	Mean site index
	Number	
A2 weak, C sandy, acid, sands and fine sands, xeric	8	47.6
A2 weak, C rock, acid, loams, xeric	18	54.7
A2 weak, C sandy, acid, loamy fine sands or sandy loams, xeric	11	54.9
A2 strong, C rock, acid, no glei, mesic	7	55.0
A2 weak, C clayey, calcareous, clays	9	55.3
A2 strong, C clayey, calcareous, no glei, drainage poor	2	55.5
A2 strong, C clayey, calcareous glei	3	56.7
A2 weak, xeric, C sandy, calcareous, sands	10	56.8
A2 weak, hydric, C clayey, calcareous	9	59.2
A2 weak, xeric, C clayey, acid, sandy loam	4	61.0
A2 strong, C clayey, acid, glei	1	61.0
A2 strong, C sandy, acid, no glei	19	61.8
A2 strong, C sandy, acid, glei	5	62.0
A2 strong, C sandy, calcareous, no glei	14	62.1
A2 weak, xeric, C rock, acid, sands	5	62.8
A2 weak, xeric, C sandy, calcareous, sandy and fine sandy loams	3	63.3
A2 weak, hydric, A_0 thick	1	64.9
A2 weak, hydric, A_0 thin, C clayey, acid	1	66.0
A2 strong, C clayey, acid, no glei, sandy loams and heavier	24	66.7
A2 weak, hydric, A_0 thin, C sandy, calcareous	5	68.4
A2 strong, C clayey, calcareous, sandy loams, and heavier, no glei	66	68.9
A2 strong, C sandy, calcareous, glei	5	71.0

Table 11.--Relation of site index for aspen to soil types[1] in Minnesota; after Kittredge (45)[2]

Very poor sites (s. i. below 50)	Poor sites (s. i. 50 - 60)	Medium sites (s. i. 60 - 70)	Good sites (s. i. 70+)
Emmett l	Ontonagon c	Chilgren c l	Potamo l s
Cass Lake l f s	Omega l f s	"Cook" s l	Granby c l
	"Boundary" l	Dora Lake f s l	Hibbing si l
	"Rock" l	Swan si l	Freer si c l
	"Border" f s l	Todd s l	Nebish l f s
	"Rock" c l	Rabey f s	Nebish l
	Marquette l s	"Boundary" l s	Rockwood l
	Milaca v f s l	Munger v f s l	
		Peat	
		Bearden f s l	
		Sebeka l s	
		Bluffton l	
		"Orr" s	
		Cloquet v f s l	
		Taylor v f s l	
		Taylor c l	
		Beltrami si l	

1/ Quotes indicate unnamed soils given temporary names by Kittredge.

2/ Abbreviations are:
- c - clay
- f - fine
- l - loam or loamy
- s - sand or sandy
- si - silt or silty
- v - very

A study of the growth of quaking aspen in Wisconsin and Minnesota as affected by soil properties and fire was reported by Stoeckeler in 1948 (75). Soils samples were collected on 29 plots; site index and volume data, complete soils descriptions, and other information were also obtained. Tests for pH and for silt plus clay content were made on all samples, and detailed nutrient analyses were run on five complete profiles representing each of the five aspen site classes. Stoeckeler concluded that soil texture, expressed as percent of silt plus clay, and the presence or absence of limy subsoils were important factors in determining the growth rate of aspen. Growth curves for five soil-site classes were constructed, showing the relation of these variables. A condensation of this information in table form is given here (table 12). These data are based on plots with water tables too deep to affect growth or moisture conditions.

Table 12.--Yield of aspen as related to soil texture and subsoil reaction; after Stoeckeler (75)

Soil or site class	Average silt plus clay content of solum (A + B zones)	Reaction of subsoil or parent material	Net merchantable yield of aspen at 40 years
			Cords
I	Over 35%, but less than 20% clay	Calcareous	32
II	Over 35%, but less than 20% clay	Acid	26
III	20 to 35%	Acid	19
IV	10 to 20%	Acid	13
V	Under 10%	Acid	5

Abundant calcium and probably other nutrients in these soils evidently contribute to the greater longevity and soundness of aspen. From studies in Wisconsin and from verbal reports of foresters in Ontario, it appears that some soils with slightly acid subsoils but devoid of free carbonates may still have enough calcium to meet the optimum needs and may approach or equal the yields indicated for Class I soils.

Podzolic loams and silt loams with limy substrata such as occur in the gray drift portions of Minnesota (now recognized as the Gray Wooded soils) are believed by Stoeckeler to be the best aspen sites. Similar soils in Wisconsin were also found to be good sites.

On the several plots where bigtooth aspen (Populus grandidentata Michx.) was a component of the stand, Stoeckeler found that this species requires a less fertile soil for good growth than quaking aspen. Loamy sands will produce good yields of bigtooth, and the best stands seem to occur on sandy loams. This finding suggests that care must be taken to avoid mixtures of the two aspens when studying the site requirements of either.

A study of the growth of quaking aspen in relation to ground water and soil organic matter was reported by Wilde and Pronin (86) in 1950. Their work was done on the poorly drained sands of central Wisconsin. On these soils, where depletion due to fires, logging, drainage, and farming is said to be serious, aspen height growth correlated closely both with depth to ground water and with soil organic matter. A "nomograph" (alignment chart) was constructed for the prediction of height growth, yields, and site index from percent of soil organic matter and depth to ground water. The simplicity of growth factors in this instance is ascribed to the sterile nature of these highly siliceous soils, and to the scarcity of nutrients in the "lean" ground water.

In the past few years a number of investigators have reported the results of soil site studies for species other than aspen. While they do not have a direct bearing on the aspen site problem, it will be worth while to review a few of them briefly to point out the approach used and the results obtained.

Coile (21) made a study of soil factors in the growth of loblolly and shortleaf pine on the Piedmont Plateau. Topographic position was classified as ridge, slope, lower slope, or bottom. Variables tested were: thickness of the A horizon, combined thickness of the A and B horizons, ratio of silt plus clay to the moisture equivalent, and imbibitional water value of the B horizon. He also correlated products and squares of these primary variables. Significant variables were thickness of the A horizon, ratio of silt plus clay to the moisture equivalent of the B horizon, the second power of the latter variable, and imbibitional water value of the B horizon.

In 1949 Tarrant (76) reported research on Douglas-fir site quality and soil fertility in the Pacific Northwest. He summarizes his findings as follows:

> No statistically significant relation was found between site class and values obtained from laboratory determinations of soil reaction, silt-plus-clay content, total nitrogen, available phosphorus and potash, base exchange capacity, replaceable calcium and magnesium, and organic matter. In general, the nutrient content of forest soils of the Douglas-fir region appears to be too high to constitute a limiting factor in tree growth.

Another study of Douglas-fir site quality, this time in relation to physical soil properties, was published by Gessel and Lloyd in 1950 (28). Using site index as a criterion, they found that on the Pacific slope of northwestern Washington growth increased with changes in soil texture from coarse to light to medium. Heavy-textured soils were not included in the study. Depth of soil was an important factor for soils underlain by hardpan or bedrock. Site index on the same soil profile and texture group was found to be related to mean annual precipitation. Site index on soils increased with precipitation up to 40 inches. Above this amount site index decreased for coarse-, fine-, and medium-textured soils, but increased up to 60 inches of precipitation for soils underlain by an impeding layer.

Gaiser (27) studied the growth of loblolly pine on the Virginia and Carolina coastal plains. He found that depth to impermeable subsoil horizons and the imbibitional water value of the least permeable subsoil horizon affected growth. The mean site index for loblolly, the imbibitional water value, and the average depth to the least permeable horizon were computed for each of 8 or more soils series. Deep profiles and a high imbibitional water value go with the best sites.

Youngberg and Scholz (89) report an interesting study of the growth of oak in the driftless area of southwestern Wisconsin in relation to soil fertility. Using volume of average dominants at 100 years as a criterion, they tested the relation of growth to pH, organic matter, texture, base exchange capacity, total replaceable bases, available phosphorus, and available potassium. Soil samples were collected from the surface with a 7-inch tube. The results indicated that "growth is conspicuously correlated with the content of total replaceable bases. This is undoubtedly because replaceable bases reflect not only the deficiency of nutrients in sandy or eroded soils, but also the harmful excess of carbonates in soils of limestone rocklands." Their work suggests that reasonably reliable forest soils data can be obtained by using the recently developed methods for rapid determinations of reaction, organic matter, and base exchange capacity. Individual values for pH, organic matter, exchangeable calcium, and exchangeable magnesium are closely related to site quality, but available phosphorus and potassium failed to show a significant trend.

Recently Coile (22) published a summary of forest soils research in the United States. This work contains a section on aspen site studies in the Lake States. He includes the work of Kittredge (45), Stoeckeler (75), and Wilde and Pronin (86). In a resume of principal soils factors that have been related to tree growth Coile lists the following:

a. Depth of surface soil (A horizon), depth to least permeable layer, depth to mottling.

b. Total depth of soil.

c. Physical nature of subsoil, least permeable layer or substratum as it influences water movement, aeration, and water availability, or mechanical hindrance to root growth.

d. Surface soil physical properties--notably pore space and texture.

e. Organic matter, as it influences moisture, aeration, soil organisms, and nitrogen.

f. Chemical properties; fertility is most apt to be limiting on deep excessively drained siliceous sands in humid climates. In such cases the fertility factor is usually confounded with adverse physical properties and a low water table, he states.

Other site factors listed are climate and length of day, aspect and exposure, topography and water table, and surface geology.

In an article published last year, Wilde (87) discusses the significance of soil reaction (pH) to forest growth. He acknowledges the influence of reaction on soil organisms, the availability of certain nutrients, and soil structure, but points out that the concentration of hydrogen ions is of minor importance to plant growth in the presence of an adequate supply of available nutrients. The unfavorable effect of strongly alkaline soils is due more to the unavailability of certain nutrients and the consumption of nitrogen by micro-organisms, than to the hydroxyl ions as such, he believes. The validity of reaction optima for various trees is questioned. The occurrence of calcareous podzols and of very acid mull soils is quoted as proof of the secondary importance of reaction.

The Chemical Composition of Plant Tissues as a Clue to Site Quality

If chemical fertility factors are important elements of site quality, presumably their level of availability might be reflected in the chemical composition of plant tissues from the areas in question. This line of soil-site research has been used to a very limited extent in forestry to date. Alway, Kittredge, and Methley (2) made a study of the composition of litter on Star Island in Cass Lake where maple-basswood, white pine, red pine, and jack pine types all occur on the same soil type. For site research, the significance of this study lies in the fact that different species were found to incorporate the various elements into their tissues in different proportions, despite the fact that the soil parent materials were the same. Freshly fallen leaves, litter, duff, and leaf mold were analyzed separately in each type. An increase in the percentage of ash, lime, and nitrogen, and a decrease in acidity were found for all four types in passing from litter, to duff, to leaf mold. The maple-basswood samples carried about five times the percentage of lime and nearly twice as much nitrogen as was found in the samples from the jack pine and red pine areas.

A textbook on forest soils by Wilde (82) has this to say on the subject of tissue analysis: "The composition of plant tissues reflects to a considerable degree the supply of available soil nutrients. Therefore, the analysis of the entire seedlings or the foliage of trees may indicate the deficiency of certain nutrient elements or their unbalanced proportion."

Wilde and Paul (83) analyzed samples of aspen wood from nine sample plots on five different soil types in Wisconsin. Site index and growth rate of aspen, and chemical composition of the soils on each site were determined also. Only very minor differences in wood chemistry appeared to be attributable to soil fertility. They concluded that pulp yields from poor sites compare favorably on a cord basis with yields from good sites; i.e., a cord of poor-site wood will produce about the same amount and quality of pulp as a cord from a good site.

Their study was not designed primarily to determine the effect of soil fertility or physical properties on aspen growth, but they did have some data on this subject also. They conclude that the best rate of growth was observed on well-drained sandy loams. Other soils, including loams, produced lower yields. Well-drained coarse sands produced the lowest yields, corresponding to site index 45. Also, although they did not draw any conclusions on this score, an inspection of their data on fertility indicates some relationships between growth rates and organic matter, base exchange capacity, and exchangeable calcium and magnesium. Because the same type of work is being done in Minnesota these data are included here (table 13).

In his textbook on forest influences Kittredge (46) summarizes the litter-site relationship about as follows:

1. The annual fall is smaller on poor than on good sites.

2. The amounts of N, Ca, P, and K returned to the surface in the litter vary with species, and with the amounts available in the soil's root zone.

3. The percentage contents of Ca, O, and N in litter are usually correlated, and tend to be less under conifers than under deciduous species, less on poor than on good sites, and less in pioneer than in climax stages of succession.

4. Fires, in destroying the forest floor, cause a total loss of the N, which volatilizes, and a conversion of the portions of Ca, P, and K bound in organic complexes to more available, soluble forms subject to rapid leaching.

5. Fires may increase the content of nitrate nitrogen in the surface of mineral soils for 1 or 2 years after the burn.

Table 13.--State of soil-fertility factors in the surface layer (0-7 inches) of soils supporting quaking aspen; after Wilde and Paul (83)

Soil type	Site index	Reaction pH	Silt and clay	Organic matter	Base exch. capacity	Available P_2O_5	Available K_2O	Exch. Ca and Mg
	Ft.		Pct.	Pct.	M.e./100 g.	Lb./acre	Lb./acre	M.e./100 g.
Well-drained outwash sand	45	5.2	7.1	1.5	2.7	40	125	1.7
Well-drained outwash sand	50	5.4	6.0	2.1	3.1	75	160	2.3
Poorly-drained siliceous sand	55	4.2	9.5	3.7	5.8	55	64	2.1
Well-drained glacial sandy loam	70	5.4	18.4	2.7	5.2	178	110	3.6
Well-drained glacial sandy loam	70	4.8	28.3	4.3	7.4	340	130	4.4
Well-drained outwash sand	60	5.9	7.0	1.8	4.2	224	108	2.7
Well-drained morainic loam	65	4.7	18.2	2.3	8.1	35	110	4.3
Morainic silt loam	70	4.9	27.0	3.7	11.8	88	97	6.1
Well-drained glacial sandy loam	80	5.0	14.1	3.6	7.7	90	96	4.9

Recently Finn (26) has used the mineral content of leaves as a means of identifying white oak sites in southeastern Ohio. He determined the N, Ca, K, and P content of leaves by chemical analysis. Nitrogen was found to be related to site index, thickness of the A horizon, and position on lower slopes; it was not related to thickness of the B_1 horizon, stand age, density, diameter growth, or aspect. Calcium was related to silt plus clay content of, and also to root concentrations in, the A horizon, but not related to thickness of horizons, site index, stand age, density, diameter growth, aspect, or slope position. Potassium and phosphorus were not related to any of the above factors, nor could interrelationships be shown for any combination of the four elements.

Aspen leaves were analyzed by Daubenmire (24) in a study of the nutrient content of litter in the northern Rockies. *Populus tremuloides*, the only dicot studied, produced litter that was definitely superior in average quality to that of any of the conifers, he states. The average composition of aspen leaves was as follows:

Total N - 0.63 percent of oven-dry weight
Total P - 0.20 percent of oven-dry weight
Total K - 1.19 percent of oven-dry weight
Total Ca - 2.19 percent of oven-dry weight

He concluded that the nutrient content of aspen leaves is similar to analyses reported by Kittredge, except that the K content was decidedly higher in the Rockies. "The general conclusion reached by many earlier workers that the chemical composition of tree leaves is primarily a characteristic of the species is borne out by this study," Daubenmire states. Nutrient content of foliage was not related to site index for ponderosa pine, he indicated, but no statement was made on this point for *Populus tremuloides*.

MOISTURE AS A SITE FACTOR

Mention has already been made of the effect of moisture in the aspen site complex. In actuality the moisture factor is so intimately tied up with soil, topographic, and climatic influences that it can hardly be considered an independent factor, but, for the purpose of emphasizing its evident relationship to the aspen site problem, it will be discussed as a separate point.

Roe (67) has concluded that the fundamental factor affecting the distribution of forests in the Lake States is not soil profile development as such, but rather the soil moisture regime as it has affected this development. In another discussion of this point he states that this is:

> ... best illustrated by aspen, whose rate of growth directly varies with soil moisture. For example, sands underlain by clay, and with a low water table are poor sites, light loams or loamy sands underlain by clay, and with the ground water

somewhat higher, are medium sites and loams with a clayey subsoil and moderately high water table are good sites for this species.

Arend and Julander (8) have really used a soil moisture approach in classifying oak sites in the Arkansas Ozarks. Good sites are found to be on deep and well drained soils on lower slopes or in valleys where moisture is abundant; medium sites are described as soils intermediate in depth, usually on upper slopes or ridges; and poor sites are mostly on shallow-soiled dry ridges.

Stoeckeler (75) has stressed the beneficial influence of shallow water tables, or "subirrigation" as he terms it, on light sandy soils. He believes that permanent water tables 3 to 7 feet below the surface will increase site index on such soils about 15 feet.

Wilde and Pronin (86), and Wilde and Zicker (84) have investigated the influence of water tables on aspen site quality in central Wisconsin. The first of these references was reviewed in the soils section of this paper because of the organic matter discussion, and it will not be repeated here. The latter work traces the influence of ground water on the distribution and height growth of aspen and jack pine on the coarse, sterile sands of central Wisconsin. Aspen was found to occur largely where ground water was within 5 or 6 feet of the soil surface. Both stocking and height growth were better where water tables were within reach of the aspen roots. Optimum depth to ground water was found to be about 33 inches; marked decreases in height growth were noted where ground water was less than 18 inches from the surface or deeper than 60 inches. It is pointed out that ground water as close to the surface as is common in this area is most apt to be present in areas of extremely light sands underlain by impervious layers. In much of Minnesota's aspen range this situation does not exist, because the soils are more often gently rolling to rolling sandy loams, and loams with water tables generally below 10 feet. In those areas where soils are similar to the central Wisconsin situation, however, the influence of ground water is undoubtedly a real site factor. From the observations of Stoeckeler, Wilde, Zicker, and Pronin, it appears that the effect of ground water probably is an element in site quality whenever the water table lies somewhere between the surface and a depth of about 7 feet.

The literature on the effects of soil texture on available moisture has already been reviewed in the section on soils, and will not be repeated here, but it should be emphasized that Kittredge, Roe, Stoeckeler, and others have stressed this factor strongly.

CLIMATE AND ASPEN SITES

Within the natural range of *Populus tremuloides* in Minnesota there are certain differences in both regional and local climates. Local climates vary over short distances, but, in a relatively level area such as Minnesota, changes are usually not of great magnitude. The difficulty of studying or applying information on local climates makes their practical value in site identification questionable for Minnesota's conditions. Hence, local climatic differences will be discussed for only two areas: the North Shore where Lake Superior has local influences, and the roughest portions of the state (principally the rock outcrop areas of St. Louis, Lake, and Cook Counties, and a few of the moraine areas).

The regional climatic pattern in Minnesota's aspen range is well documented by U. S. Weather Bureau records. Detailed maps, showing mean annual temperatures, temperature extremes, monthly temperatures, annual and monthly precipitation, snowfall and snow depths, length of frost-free season, dates of earliest and latest killing frosts, average sky cover and sunshine, and many other characteristics of the state's climate, are available in the sections on climate by Reed (65) and Kincer (42) (43) in the Atlas of American Agriculture, and in Livingston and Shreve (52), the 1941 Yearbook of Agriculture (78), and undoubtedly in a great many other Weather Bureau publications. Based on these references, some of the major climatic variations within the commercial range of aspen in Minnesota are as follows:

1. Mean annual temperature decreases from about 42° F. in the south to 35° F. in the north.

2. The average frost-free growing season varies from about 140 days in the south and near Lake Superior, to only 100 days in certain northern areas.

3. Mean annual precipitation varies from a maximum of 30 inches in the southeast and extreme northeast, to about 20 inches at the prairie margin in northwestern Minnesota.

4. Mean annual snowfall varies from a maximum of over 70 inches in the northeast to only about 35 inches at the southern and western limits of extensive aspen forests.

5. Daytime relative humidity (especially in the afternoon) during the growing season averages 5 to 10 percent lower at the southern and western limits of aspen than in the northeast.

6. Average summer temperatures (June through August) vary from 60° F. in the northeast to about 68° F. at the prairie margin in the southwest.

7. Temperature extremes vary with maximums from about 110° F. at the prairie margin in the southwest to 100° F. in the extreme northeast, and with minimums from -55° F. in the north to -40° F. at the southern limit of commercial aspen.

8. There is about a half-hour difference in day length between the Canadian border and the latitude of St. Paul during most of the growing season.

9. The extreme northeastern counties receive about 60 percent of total possible sunshine during the growing season, while the western and southern limits of aspen forests receive approximately 70 percent.

Some of the climatic features summarized above indicate rather wide variations within the commercial aspen range, while other characteristics may appear (at least superficially) to differ only slightly from northeast to southwest. It should be borne in mind, however, that the combined effect of these climatic factors is sufficient to cause a marked change in the natural vegetation of the state. Passing from northeast to southwest the vegetation runs from spruce-fir, aspen, birch, and the northern pines (approaching a boreal forest composition), to mixed hardwood-conifer associations; then, near the prairie margin, to nearly pure deciduous forests of oak, maple, basswood, and aspen; and, finally, to natural grasslands where trees grow only in scattered groves or along stream courses. Aspen occurs throughout all of this forest region--even out into the prairies in the typical aspen thickets.

The possible effect of these climatic differences on the growth of important forest species in Minnesota has not been investigated so far as can be determined. However, a number of workers have studied the distribution of forest types in North America as related to climate, and the general correlation of forest types with climate has been well established. Among these works the following might be mentioned: Merriam (56), Transeau (77), Pearson (63), Livingston and Shreve (52), Schantz and Zon (69), and Bates (12).

The boundary between the Transition and Canadian zones, as defined by Merriam (56), passes across the southern portion of the state's forest area, marking the change from northern coniferous forests to the vegetation of the Central Hardwood region. Inspection of Munns' (57) map of the range of *Populus tremuloides* indicates that aspen is primarily a member of the boreal forest, although the extremes of its range extend into the Central Hardwood region and the Transition zone of Merriam.

The "precipitation-evaporation ratio" of Transeau (77) seems to define fairly well the main range of aspen in Minnesota. The value 1.00 (an equality of precipitation and potential evaporation) roughly follows the natural prairie margin in western and southern

Minnesota--a line which is also the limit of commercially important aspen stands.

Unfavorable climatic factors may tend to reduce aspen yields in a belt around the natural southern and western limits of the species in Minnesota. Work on aspen and other species in mountainous areas has shown a definite climatic influence in site quality, but whether similar effects are associated with a change from prairie to forest climate in a flat region such as Minnesota, is not definitely known.

In the Central Rockies, Baker (9) notes that the lower limit of the aspen type coincides roughly with a mean annual temperature of 45° F. (or about that of Wabasha County, Minnesota). In describing aspen sites in the Rockies, Baker states:

> In general site quality 1 is found on moist flats having deep, perhaps rather heavy soil ... Site quality 2 includes the great bulk of the stands of good quality in the Central Utah region. In general these sites are relatively not so well watered, and are more likely to be on slopes, as compared with site quality 1... Site quality 3 includes situations similar to quality 2 as to topography, but usually at elevations below the best altitudinal zone for aspen. It also occupies steep slopes within the optimum zone... Site quality 4 is found nearly everywhere at the lower limits of aspen, and also on south slopes at higher elevations. It usually bears a dense pole stand which rarely develops trees of saw-log size. Site quality 5 includes great areas of aspen on south and west slopes, on poor soils, and particularly at elevations above the zone of best development (usually of the "Thicket type"--less than 40 feet tall at maturity).

The above quotation shows that Baker relies heavily on altitudinal (and hence climatic) factors in describing aspen site quality in the Rockies. The lower limits of the species (comparable to our southern and western limits) are poor sites, as are also the hot, dry south and west slopes and the very high and cold sites. Similar work with other species is reported by Pearson (63), Bates (12), and Gessel and Lloyd (28).

FIRE AS A SITE FACTOR

An early investigation of the effect of forest fires on soil productivity in Minnesota was reported by Alway and Rost in 1927 (1). Their conclusions were as follows:

> In the case of the most heavily burned over forest the loss of organic matter varied from 7 to 26 tons per acre and of nitrogen from 450 to 1,500 pounds per acre, the losses of both being confined to the surface layer of organic residues. Even where the leafmold had been entirely burned off no evidence was found of any loss of nitrogen or organic matter in the uppermost portion of the mineral soil, or of any alteration in this except in some places a slight reduction in acidity due to the action of lime in the ash ... the loss in productivity of mineral soils traversed by forest fires is dependent upon the completeness of the destruction of the forest floor and the consequent loss of nitrogen, and not upon changes in the underlying mineral soil.

Shirley (72) found that light burning stimulates both the numbers and height growth of aspen suckers, at least for the first season. The difference is ascribed to greater heat absorption of the fire-blackened soil surface on burned areas.

In 1948 Stoeckeler (75) reported a study of the effect of soil properties and fire on the growth of quaking aspen (the soils phases of this publication have already been reviewed). He found that "repeat burns in established aspen stands caused a marked reduction in site index ...," amounting to 17 feet or more, depending on the severity of the fire. Stoeckeler believes that fire history is one of the most important factors influencing site quality for aspen, a possibility overlooked by previous investigators. The effects of fire are summarized as follows:

> It reduces growth, causes fire scars that open the way for decay, reduces stocking and hence volume, and causes site retrogression and early senility and breakup of the stand. Fires consume all or parts of the litter, F and H layers, thus destroying much of the vast network of fine feeding rootlets in the lower portions of the organic layer. The H layer has the most abundant rooting of any part of the soil profile. The burning of the organic layers reduces the amount of nitrogen for plant growth and decreases infiltration and water holding capacity. Fires also open the stand to invasion by competing weeds and grasses; the latter appear to prevent optimum stand development.

The second aspen rotation in the Lake States may be of better quality than the present in many areas due to better fire protection, Stoeckeler believes. Severe fires and repeat-burns are more serious on the lighter soils, he points out, because on these sites the organic matter is badly needed, and their native productivity is low even without the injurious effects of fire. Curves showing the reduction in site index due to fires on various soil classes are presented; these data are summarized in table 14.

Table 14.--The effect of fire on aspen site index on soils of various textures; after Stoeckeler (75)

Average silt + clay content of A + B horizons	Average site index of aspen		
	Unburned soils	Light to moderate burns	Severely burned sites
Percent	Feet	Feet	Feet
10	55	45	40
20	70	53	45
30	77	64	60
40	80	70	65
50	82	75	70
80	78	72	67

SITE QUALITY RELATED TO ASPEN DISEASES AND INSECTS

At least two types of disease have been discussed in regard to the aspen site problem by various writers; they are heart rots and cankers.

Schmitz and Jackson (70) reported the earliest detailed study of heart rots. They found the fungus, *Fomes igniarius* (L.) Gill., responsible for true heart rots, and *Fomes applanatus* (Pers.) Gill. to be the cause of so-called "butt rot." Due to these two fungi, nonmerchantable volumes were found to increase from 4.8 percent of the total tree volume at 30 years, to 20.5 percent at 70 years. Schmitz and Jackson suggest, from data regarding the prevalence of decay in trees of different sizes, that the quality of site makes little or no difference.

Hypoxylon pruinatum (Klotsche) Cke., a serious canker of quaking aspen in Minnesota, was first reported as a disease on this tree by Povah (64) in 1924. This disease frequently attacks the main stem of aspen, and when it does, girdling may eventually occur, killing the entire tree, or at least those portions above the girdle. Many of the earlier discussions of the disease-site question failed to distinguish between losses due to heart rots, butt rots, and Hypoxylon, but most observers believed the disease problem was more serious on poor sites than on good. Kittredge and Gevorkiantz (44) may be quoted as follows:

> The question of whether decay is more serious on poor sites than on good sites has not been answered. There is a general impression among those familiar with the region that the aspen goes to pieces earlier from decay or some other cause on poor sites than on good sites. This impression is confirmed by the distribution of the measured plots in relation to

age and site index. In spite of the fact that a special attempt was made to obtain data representative of all the age and site index classes, none of those with site index less than 50 were more than 45 years old, those of site index between 50 and 55 were less than 60 years old, and the few plots over 74 years old had site indexes over 65.

In 1936, Robert Anderson (5) reported Forest Survey data which suggested that cull trees were most common on sandy pine lands. Zehngraff (91) has summarized data (table 15) indicating the extent to which cull reduces merchantable sawlog volumes on good, medium, and poor sites.

Table 15.--Usable sawlog volumes at various ages (percent);[1/] from Zehngraff (91)

Site class	Age of stands								
	40	45	50	55	60	65	70	75	80
	Percent of gross volume merchantable								
Good[2/]	90	87	85	82	76	68	57	47	25
Medium[3/]	83	79	73	62	50	38	11	..	..
Poor[3/]	75	54	33	14	..	..	..	..	..

1/ Volumes are by the Scribner rule for trees 7 inches d.b.h. and larger to a minimum top diameter of 6 inches inside bark and a minimum log length of 8 feet.

2/ Based on scale records in logging studies in northern Minnesota.

3/ Based on estimated cull percent in unmanaged stands.

This table shows the rapid increase of cull with age on the poorer sites. The specific wood-destroying organisms responsible for cull on the various sites are not identified, but undoubtedly the two species of Fomes were involved to a large extent on all sites. In his 1949 Journal of Forestry paper, Zehngraff (92) again expressed the opinion that satisfactory information on the relation of age and site to cull was not available, but he again stated that the disease problem is more serious on poor sites than on good.

More recently Ralph L. Anderson (3 and 4) has reported on a detailed survey of Hypoxylon canker in the Lake States. He has concluded that incidence of this disease is not correlated with site index, tree vigor, or any of the environmental factors studied which influence tree vigor. He does believe, however, that the effect of the disease is more serious on poor sites, because the slower-growing trees are exposed to infection longer before reaching merchantable size. He points out that, assuming equal initial stocking, the same rate of stem depletion due to this disease would be more serious on poor sites than on good, because at any given age the poor sites require more trees per acre for full yields due to slower growth rates and consequent smaller stem volumes. Anderson did find a strong correlation between low stand density and high incidence of infection. This suggests that stands with low stocking due to repeated fires or other factors would tend to have high canker losses, if there is a cause-and-effect relationship between low density and infection. His data on fire history indicate that severe or repeated fires may create conditions favorable to Hypoxylon, Anderson reports, although the trend in this direction was not particularly strong.

Another point of interest came out in Anderson's study. It appears that extreme northern Minnesota has a much lower incidence of Hypoxylon than does the rest of the state, or the Lake States as a whole. The low incidence area, including Koochiching, northern Itasca, northern St. Louis, and northern Lake Counties had killing cankers on only 1.8 percent of the living trees, while incidence for the remainder of the region varied from 4.8 to 6.1 percent. For some reason, incidence of this disease is evidently less in the gray drift portions of Minnesota. Anderson warns, however, against concluding that this difference is attributable to the soil parent material, since no available evidence supports such a contention. The low and high incidence areas also differ in latitude and probably several other important respects, he points out.

Bacterial "wetwood" is another pathological condition common in quaking aspen, that may possibly be related to environmental factors. "Wetwood" is objectionable to pulp mills because of added bleaching costs, and in lumber because it contributes to warping and collapse. Although there has been some research on this problem, there is as yet no literature definitely linking wetwood to specific site factors.

A number of serious insect pests are known to infest quaking aspen, but a definite tie-in to the site problem has not yet been established. Hodson (38) made an ecological study of the forest tent caterpillar (Malacosoma disstria Hbn.) in Minnesota. His bulletin contributed a great deal of basic information on this defoliator which has been epidemic at intervals of 10 to 15 years. Batzer, Hodson, and Schneider (13) reported on a study of the effect of the 1950 to 1954 epidemic on the growth of quaking aspen. They found a direct relationship between frequency and severity of defoliation and radial increment. Both reduction of radial growth and crown dieback were found to extend into succeeding non-defoliation years. However, not a single dead aspen was found whose death could be attributed solely to the forest tent caterpillar. They state that "observed differences in stand age, density, and site characteristics including slope, aspect, and soil moisture condition appeared to have no marked influence on the results of defoliation..."

In 1954 Graham and Harrison (29) reported findings on the relationship between insect attacks and Hypoxylon canker in Lower Michigan aspen. They observe that stand deterioration may begin as early as 25 to 35 years on poor sites in southern Michigan. Hypoxylon canker is said to be the most destructive disease of quaking aspen in this area. On 416 sample plots, 22 percent of all quaking aspen and 4.8 percent of all bigtooth aspen were cankered. Of 138 cankers where it was possible to identify the infection court, 95 percent are reported to have originated in insect injuries. In the 1952 cankers, half of the infections were linked to wounds caused by the poplar borer (*Saperda calcarata* Say.). In 1953, with a decline of this insect, only 10 percent of the infections were attributed to the poplar borer. A metallic woodborer, *Dicerca tenebrica* Kby., was reported to be responsible for most of the cankers in low-quality aspen stands. This beetle is said to be a sun loving insect, and breeds only in exposed trees. Less significant as sources of infection were species of Agrilus and several Lepidoptera. With the beetles the infection court was identified as the egg-laying niche made by females during oviposition, or larval cavities made soon after the eggs hatch. No literature is available linking insect attacks to the Hypoxylon problem in Minnesota.

It is evident from this discussion, and from the review of growth and yield data, that most research workers have noted more rapid decadence and earlier break-up of aspen stands on poor sites than on good sites, but there is still relatively little quantitative data to show just how diseases and insects contribute to this accelerated decline on the poor sites.

THE "TOTAL SITE" APPROACH

In the past few years, several site workers have been impressed with the variety of factors that can affect the yields of given species, and a new approach to the site problem has developed. G. A. Hills of Canada is a principal exponent of the new school of thought. Hills states (37) that:

> ... in the past sites have been classified by ground vegetation, forest cover, climatic soil types, single soil characteristics, land form, and other features. No single feature or feature group can in itself adequately define site. Ground vegetation types are not adequate unless they are considered in relation to forest cover types, stand history, regional climate, local relief, and so on.

He has devised a scheme of classifying site factors, using symbols for each major element. Essentially Hills' system consists of combining into formula form the significant factors of site in given areas. These areas may be large or small depending on the use to which the data will be put. A site map of the given area can then be prepared. This approach classifies the site *per se*--without reference to individual species. Brown (17) has recently reported on work using Hills' system. In order to predict yields for given species by this system, studies must be conducted to determine the potentials of each site for the given species.

In 1952 Bedell and MacLean (14) published a report on certain phases of the application of Hills' system to an area south of Lake Nipigon in western Ontario. The area covered is Halliday's (32) B-9 subregion of the boreal forest, which extends to within a few miles of Cook County, Minnesota. The forests and site conditions in the Nipigon area are quite similar to those of northeastern Minnesota, although the boreal species are more strongly represented in the former.

Quaking aspen is one of the species covered in the Nipigon site survey. The site classification used in this study is based on an 11-step rating scale for "moisture regimes," and a 10-step scale of soil permeabilities. For practical purposes some 16 "site types" were recognized in the Nipigon survey. These sites range from saturated bogs at one extreme to barren rock outcrop at the other. Available soil moisture is the foundation of the system. Each site type is also identified by its characteristic ground cover. A total of 251 plots were taken in the "hardwood" and "mixedwood" types where aspen is common. A brief quotation follows describing each of the six site types for which site indexes of quaking aspen are given:

Site Type A: ... usually found on gentle slopes of upland till, but it may be found on soils which are lacustrine or fluvial in origin... After a fire, pure aspen stands usually come in... The soil is moist and over 3 feet in depth. It varies in texture from fine sand to clay ... Cornus-Aralia-Aster is the typical ground-cover pattern.

Site Type B: The characteristic location is on gentle lowland slopes. These are usually lacustrine or fluvial in origin, but may be morainic or deltaic. The climax stand is a mixture of balsam fir, black and white spruce, trembling aspen, and white birch, with scattered cedar, although balsam poplar may be fairly abundant... The soil is moist--more moist than on Site Type A --and varies in texture from fine sand to clay. It is always more than 3 feet in depth. This site type is very productive, and it grows the finest aspen stands in the forest section. The Cornus-Aralia-Aster ground-cover pattern is associated with hardwood and mixedwood stands, and the Hypnum-Hylocomium pattern is found under black spruce stands.

Site Type C: This site type is usually found on moderate to steep till slopes... Fire stands are jack pine or trembling aspen although, in some cases, white birch may come in. The soil is over 3 feet in depth, somewhat dry, and may vary from fine sand to clay. Jack pine is at its optimum on this site type... The Cornus-Aralia-Aster ground-cover pattern is most common.

Site Type E: Kames, eskers, outwash plains, terraces, and light recessional moraines are the customary locations, and the slopes may be moderate to almost level... The soil is 5 or more feet in depth, and somewhat dry to somewhat moist sand or gravel ... ground-cover patterns are Cornus-Aralia-Aster, Cornus-Aralia-Alnus crispa, and Hypnum-Hylocomium.

Site Type I: ... Usually found on outwash plains, tops of kames or eskers, dunes, or steep till slopes. Owing to its susceptibility to fire, jack pine stands predominate and aspen may sometimes occur... The soil is dry, but may be of any texture. Cornus-Aralia-Alnus crispa is the typical ground-cover pattern...

Site Type R_1: The soil, varying in texture, has a depth of less than 1 foot over fairly level bedrock. The controlling growth factors are the shallowness of the soil and the periodic lack of water ... Two ground-cover patterns are common, Cornus-Aralia-Alnus crispa with mixedwood stands and Hypnum-Hylocomium with softwood.

The average site index of quaking aspen on each of these site types is given in table 16. These relationships check quite well with the trends and observations on soils and moisture relations reported by Kittredge (45), Roe (67), Stoeckeler (75) and others. Volume yields in cubic feet are predicted (for all species) on each site type using "Stand Density Indexes" to adjust for stocking variations. Further refinement of these predictions is planned when the permanent plots are remeasured to obtain actual growth data.

It might be pointed out that many recent site investigations have tended in a direction similar to the thinking of Hills and the advocates of his system. The single-factor approach is now generally recognized as being inadequate, and most of the newer systems of site classification are taking into account as many variables as possible. Some other writers that have used or advocated a more generalized approach include Coile (21), Gysel and Arend (31), Lunt (54), Veatch (79), and Rowe (68). A few remarks by the latter might be quoted:

> Site is not a simple concept. When studied in relation to forest growth it is found to be more than climate and topography and soil. It includes not only these and other environmental features, but also communities of plants and animals. More accurately it is found to be the dynamic and complex interrelation and interaction of all features, inorganic and organic, past and present, which have resulted in the given forest stand.

Table 16.--Average site index of quaking aspen on six site types in the Nipigon region of Ontario; after Bedell and MacLean (14)

Site type	Total height of dominants at 50 years	Total height of dominants at 100 years
	Feet	Feet
B	70	95
A	68	91
E	60	81
C	59	78
I	57	74
R_1	40	62

PLANT INDICATORS OF SITE

All of the methods of evaluating site so far discussed have used characteristics of the forest stand or environmental factors as a means of defining or explaining site quality. A final approach to the site problem uses neither, but looks to the minor vegetation and, in some cases, the entire community of plants as indicators of site. This school of thought is based on the belief that plant communities are not accidental assemblages of plants, but reflect the entire range of site factors. The theory holds that each habitat (therefore, all possible sites) tends to have a distinct natural vegetation which, if adequately described and identified, can be used to define site quality.

The "plant indicator" approach, as it has come to be called, got its impetus in forestry from the work of the Finnish forester Cajander (19). A complete set of indicators, defining the principal site types or "forest types" of Finland, was worked out by Cajander. His system seems to have been quite useful in that country, and is still being applied by many Finnish foresters.

In North America the plant indicator approach has been attempted in several regions, with varying degrees of success. Heimburger (34) has developed a set of site types or "forest types" for the Adirondack region of New York, and has applied his findings to portions of Canada as well (36). Ilvessalo (39) has attempted to apply the Finnish system in the United States, and has also studied the occurrence of Cajander's types on various soils in Finland (40). The latter study showed that these types definitely are not confined to single soil types, although certain types tend to be strongly represented on some soils and very little on others. Hansen (33) has shown that indicators have some relation to jack pine site quality in Minnesota. More recently Linteau (51) and Long (53) have reported on work with indicators in eastern Canada, and Westveld (80) has worked with climax vegetation, soils, and indicators in the northeastern states.

Plant indicators appear to be of some value in identifying aspen sites in the Lake States. Kittredge (45) analyzed the relation of site index to 16 natural community plant indicator groups in Minnesota and Wisconsin and obtained a correlation ratio of 0.761, or practically the same correlation obtained by using soil-profile groups (see section on soils). Detailed lists of the plants characteristic of some of his natural communities are given in Kittredge's paper. The 16 communities, together with their mean site indexes, are as follows:

	Natural community - indicator group	Mean site index
1.	Norway pine	52.1
2.	Tamarack-black spruce	53.0
3.	White-cedar	55.1
4.	Jack pine	55.4
5.	Spruce-balsam, jack pine	58.0
6.	White pine, jack pine	58.5
7.	White pine, spruce-balsam	59.2
8.	Oak	62.8
9.	Spruce-balsam, maple	63.4
10.	White pine, swamp	63.9
11.	Maple, Norway pine	65.4
12.	Maple, white pine	67.5
13.	White pine, maple	67.8
14.	Maple, spruce-balsam	68.8
15.	Maple, swamp	69.0
16.	Ash-elm	69.6

Kittredge noted that hardly one of the individual plants was constantly or exclusively characteristic of the natural community to which he assigned it, but, by studying the frequency of all species on a given plot, the community which it most nearly resembled could usually be determined. The indicator value of a large number of individual species was tested, but it was found that "on the whole, the conclusion seems justified that individual species do not characterize the site index of aspen specifically enough to be used for prediction with any degree of confidence, even within a range of as much as 10 site index units."

Roe (66) (67) has made an analysis of indicators for aspen in the Lake States, and obtained results very comparable to those of Kittredge. A large number of native plants were classified and analyzed for indicator value in distinguishing sites suitable for certain natural cover types. The lists were narrowed down to those species which were either constant and exclusive, constant only, or exclusive only to the given types. A list of plants that met these criteria is given for each of the following forest types (67): pine (i.e., jack and Norway), oak, northern hardwood, white spruce-balsam fir, bottomland hardwoods, and conifer swamp. Roe then analyzed aspen site quality for each of these forest types, based on a large number of field plots on which site index for aspen and vegetation data were obtained. The relationship of site to type was determined as indicated by both the existent under vegetation and by remnants of the original forest (table 17).

Table 17.--Aspen site index in relation to natural forest types; after Roe (66)

Natural type indicated by under vegetation	Mean site index	Natural type indicated by remnants of old forest	Mean site index
Northern hardwoods	73.2	Bottomland hardwoods	71.0
Bottomland hardwoods	70.8	Northern hardwoods	70.9
White spruce-balsam	69.5	White spruce-balsam	65.4
Oak	66.9	Oak	62.8
Conifer swamp	66.0	Pine	61.0
Jack pine, Norway pine	62.1	Conifer swamp	59.0

More recently Sisam (74) has reported the result of forest site studies at the Petawawa Forest Experiment Station in Ontario, using Heimburger's site types (35). Six site types on which aspen occurred were distinguished. These were named for their key species as follows:

1. Trillium
2. Aralia
3. Aster-Corylus
4. Maianthemum-Corylus
5. Aster-Gaultheria
6. Vaccinium-Myrica

Stands of 60-year-old aspen were located on as many of these types as possible and their yields determined by volume table and by actual logging. Volume table figures for the first four of the above sites were as follows (table 18):

Table 18.--Volume per acre in 60-year-old aspen stands by site-types; after Sisam (74)

Site type	Volume cu. ft.	Number trees	Volume per tree cu. ft.
Trillium	4,210	370	11.4
Aralia	5,020	544	9.2
Aster-Corylus	3,870	738	5.2
Maianthemum-Corylus	5,740	969	6.0

The Trillium site is considered the best aspen site, and the Vaccinium-Myrica and Aster-Gaultheria sites are very poor, it is reported. On the basis of height curves, Sisam indicates that the Aralia site rated highest, but the Trillium site develops the highest volumes per tree, and yields the largest merchantable volumes. Sisam observes that the Trillium site type is characteristic of the northern hardwood climax, and the Aralia type is associated with a white spruce-balsam fir climax. The Petawawa Station lies in a tension zone between these two climaxes.

The findings of Sisam are in general agreement with those of Kittredge and Roe, although their approaches were somewhat different. It appears from the work of these three investigators that the best aspen sites are indicated by a rich herbaceous vegetation characteristic of the northern hardwood or swamp hardwood types; and the poorest sites are characterized by either very dry site indicators, such as normally go with the jack pine type, or by the conifer swamp vegetation. Oak, spruce-balsam, and white pine vegetation are somewhere in between these extremes.

The plant indicator approach appears to have given encouraging results with aspen. A note of caution in its application without further refinements seems in order, however. Many writers, notably Coile (20), have warned against the dynamic nature of lesser vegetation where major differences in forest cover occur on what appear to be otherwise similar habitats.

Disturbances such as logging, fires, or cultivation can change, at least temporarily, the plant communities present on an area. He points out that the nature of the overstory trees themselves can alter the composition of duff, humus, and upper soil layers quite considerably, and these changes may presumably be reflected in the under vegetation.

In a state such as Minnesota, where aspen occurs in zones of tension between hardwood forest and conifer forest, and between each of these and prairie vegetation, the indicator approach may have additional pitfalls. Grant (30) and Buell and Wilbur (18), and many other ecologists have pointed out the transitional nature of the forests of Minnesota. Presence of given indicator species may not mean the same thing in terms of aspen yields in the southern or western portions of the state as it does in the northeast. One obvious example of this situation might be cited. In extreme northern and northeastern Minnesota the northern hardwood community (or the Trillium site type of Sisam) occurs only rarely, but the spruce-balsam (or Aralia) community is common. If present indicators are used, presumably the best aspen sites are rare in these areas. As a matter of fact, however, some of the finest quaking aspen stands in the Lake States are present in the northern counties on sites where the indicators are typical of the spruce-balsam or Aralia types. Apparently, if indicators are to be used in Minnesota, further refinements are needed, taking account of the wide range of vegetational change within the forest areas.

SUMMARY

The foregoing literature review has touched on a wide range of factors related to aspen growth. This summary attempts to tie together the findings of the various research workers, using the same topic breakdown as the review.

Growth and Yield

1. Yields.--The range of yields from the five recognized aspen site qualities is now fairly well defined. Early estimates were much too high, especially for the poorer sites. Some disagreement is still prevalent due to varying utilization standards and differences in the amount of partially decayed wood that is accepted.

2. Site Index.--Five site index classes have been defined by Kittredge and Gevorkiantz based on the average height of dominants at 50 years. A set of curves is available for estimating site quality of older or younger stands. The consensus seems to be that site index is not a reliable guide to yields for stands less than 25 years of age. Even for stands 25 to 35 years old such factors as rot, canker, and stand break-up due to other environmental elements make the prediction of future yields rather hazardous in practice if only site index is considered. A better guide to growth and, especially, to longevity of aspen stands is evidently needed.

Soils

1. Texture.--Kittredge, Roe, and Stoeckeler found definite relationships between soil texture and aspen site quality. Many other writers working with both aspen and other species have also expressed the opinion that texture has important effects on the productivity of forest soils. One way in which texture is believed to affect growth rates is through its influence on moisture-retaining capacity. A silt-plus-clay content of 30 to 50 percent is reported to be about optimum for aspen, while the very light sands and tight clays have generally been found to make poorer sites. These findings have practical significance, because texture can be readily determined in the field. Further work can help to define the conditions under which texture becomes a key factor, and to give it proper weight in a field procedure for classifying quaking aspen sites. Texture alone does not appear to correlate closely enough with aspen growth to permit reliable site estimates based on this factor only.

2. Organic Matter.--Wilde and Pronin have demonstrated the importance of soil organic matter on sandy aspen sites. Although they are the only ones to integrate organic matter into a site classification technique, comments by other authors indicate that this factor has been considered an element in site quality by several workers. It appears that the lighter soils, particularly, are poor aspen sites when deficient in organic matter. Very little published data are available on the effect of organic matter on the heavier-textured forest soils, but this is a lead that needs further exploration.

3. Soil Chemistry.--A few studies have given indications that soil nutrients are a factor in aspen site quality. There is little direct evidence on this point, but data reported by Roe, Kittredge, and Stoeckeler suggest that soil chemistry is involved. These workers found that gray drift soils are often better sites than soils derived from the other drifts; texture, moisture, and climatic conditions, however, were not always comparable. Profile analyses reported in the literature indicate that gray drift soils frequently contain more exchangeable calcium and magnesium and possibly other nutrients than soils with similar texture but derived from red drifts. Work with some other species has shown a relationship between site quality and certain nutrients. The literature suggests that nutrients are most apt to be limiting on very sandy soils, where moisture-retaining capacity may also be unfavorable to aspen growth. Further work will be needed to settle these questions and to determine whether chemical soil properties can be used in practical site classification procedures.

4. Soil Reaction or pH.--Reaction is probably not a significant site factor in itself, but the literature indicates that pH may be a useful field guide for distinguishing the drifts, and a rough indicator of other chemical soil factors. This possibility needs to be verified by more data.

5. Litter Analysis.--Analysis of freshly fallen leaves offers a possible means of determining the extent to which aspen actually uses the nutrients available in various soils. This technique has not been reported on for aspen, but it has been a profitable line of research with some other species.

6. Soil Types.--Soil Survey maps have been used to determine whether the mapped soils can be used for site classification. The results of this work indicate that soil types, as mapped for agricultural purposes, may be used as a very rough guide to site quality, but the growth of aspen varies too much between different localities on the same soil type to permit accurate site diagnosis based on soil type only.

Moisture

Several investigators have reported on the influence of ground-water tables on aspen growth. The evidence indicates that ground water, within a range of approximately 2 to 7 feet of the surface, may substantially increase site quality, especially on light sandy soils. Water deeper than 7 feet is apparently out of reach of the rooting zone and is of no benefit, while water tables within 2 feet or less of the surface create swamp conditions, and are unfavorable to aspen, it is reported. In rolling topography ground water would be a factor only on lower slopes and in low-lying areas, but in level terrain this element of site quality may be quite important over relatively large areas. Ground water appears to be a factor that must be considered in a site classification scheme for aspen in Minnesota. It is intimately tied up with topographic position.

Climate

No research on the effect of climatic factors on aspen growth in the Lake States is reported in the literature. Reports from the Rocky Mountains indicate that site quality varies with altitude, and hence climate. There is a possibility that the range of climatic conditions within the commercial aspen producing areas of Minnesota is great enough to cause substantial differences in growth rates, longevity, incidence of disease, and other factors affecting productivity. To determine whether this is the case, weather records suggest that comparisons should be made between the northeastern counties (Cook, Lake, St. Louis, Itasca, and Koochiching) and the western and southern fringe counties, since these are the areas with the greatest contrast in climatic conditions. It would, of course, be necessary to eliminate other variables from this comparison as much as possible.

Fire

The injurious effect of repeat-burns on aspen growth has been established by Stoeckeler. In particular, his data show how the wounding effect of light surface fires may depress site index and yields. Possible long-term effects of fires in reducing organic matter content, and the consequent loss of moisture-retaining capacity, nitrogen, and probably changes in other soil properties are not so well documented in the literature. The evidence suggests that there is a long-term reduction in yield from these effects in addition to the direct injuries inflicted on wounded trees that survive the fire. The extent of such long-term effects appears to depend on the number and severity of burns. Whether decreased yields may still result in the second rotation is not clear. It appears that the effects of fire must be integrated into any comprehensive scheme of site classification for Minnesota aspen.

Disease and Insect Relationships

Losses from heart rots and Hypoxylon canker may be related to other site quality factors, although the evidence cited in the literature is very inconclusive on this point. It is abundantly clear, however, that general stand decadence and breakup occur earlier on the poor sites than on good sites. Just how this ties in with diseases and insect injuries is still not definitely known, but there are enough data on Hypoxylon losses so that this factor, at least, can be allowed for to some extent. In areas where the incidence of Hypoxylon is high, some reduction in yield estimates seems logical.

The "Total Site" Approach

The followers of G. A. Hills and others advocating an overall site classification, rather than a species-by-species approach have done a service in emphasizing the complexity of the site problem. This system is still in the process of development, but some indication of how quaking aspen sites work out is already given by the Nipigon growth and yield survey reported by Bedell and MacLean. Samples of all sites in the region were stratified into 16 "site types" based on ratings of moisture regime and soil permeability. The system used is an adaptation of that developed by Hills. Site index charts for quaking aspen were prepared for the six site types on which this species is most common. These charts indicate that quaking aspen made its best height growth on sites with somewhat moist to very moist moisture regimes, in soils with moderate to very slow permeability. In general, these better sites tended to be on gentle slopes or nearly level areas with deep loamy or even clay soils, or moist fine sands. In contrast, the poorest site types for aspen were those with dry to very dry moisture regimes, the poorest being soils with a depth of less than 1 foot over bedrock. These relationships agree very well with the findings of Kittredge, Roe, and Stoeckeler in the Lake States.

Plant Indicators

The findings of Kittredge, Roe, and Sisam on plant indicators are in general agreement, and could be integrated into a scheme for aspen site classification. The problems of using this approach for an entire state as large as Minnesota must, however, be recognized. Plant communities change sufficiently from the northeast to the south and west within the state's aspen producing area so that a single set of indicators could hardly be expected to apply in all counties. A revised set of indicators might very well be included with an overall site classification for Minnesota aspen, at least as a check against results obtained by other methods.

The Combined Effect of All Site Factors

It is clear, from the literature, that the growth of quaking aspen depends upon the interaction of a great many environmental factors. Among these, some of the most important appear to be: soil texture, fertility, and organic matter; ground water and topographic relations; fire history; diseases and insects; and possibly climate. It may not be feasible to incorporate all of these factors into a field procedure for evaluating sites, but the more that are taken into account, the better the end result is apt to be.

The primary research need now is to investigate further some of the less well understood elements, supplement the data on those factors that are already known to be significant, and combine the results into a practical guide for recognizing aspen sites.

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APPENDIX

The six tables shown in this section contain analyses of some of the common Minnesota aspen soils. The abbreviations used in the tables have the following meanings:

M.E.	=	Mil-equivalent
B	=	Base
Sat.	=	Saturation
O.C.	=	Organic carbon

Soil particle size classes:

C	=	Coarse
F	=	Fine
M	=	Medium
S	=	Sand
V	=	Very

Table 19.--Taylor silt loam (Gray Wooded) Beltrami County, Minnesota; after Beltsville data (7)[1/]

Depth (Inches)	Horizon	M.E./100 grams soil			Per- cent B. Sat.	pH	Per- cent O.C.	Size classes (percent)						
		Ca	Mg	K				Clay	USDA silt	VFS	FS	MS	CS	VCS
2 - 0	A_0	..	..	..	..	5.8	..	..	..	..	..	..	..	..
0 - 1	A_1	..	..	..	..	5.7	5.1	5.5	30.8	17.2	34.1	6.7	4.1	1.6
1 - 12	A_2	2.3	0.5	$<$0.1	67	6.6	0.26	3.3	22.5	25.0	36.3	6.5	4.4	2.0
12 - 16	B_{21}	6.7	2.2	0.2	77	6.4	0.20	16.7	24.5	16.8	27.6	7.5	4.8	2.1
16 - 25	B_{22}	9.9	3.6	0.4	77	6.1	0.19	26.7	25.8	14.0	21.6	6.2	4.2	1.5
25 - 35	B_3	..	..	..	..	5.6	0.16	26.8	25.1	13.5	21.8	6.4	4.6	1.8
35 - 46	C_2	14.2	6.1	0.2	95	7.0	0.23	22.5	30.9	13.8	20.1	6.0	4.6	2.1

1/ See page 55 for meanings of abbreviations.

Table 20.--Taylor silt loam (Gray Wooded) Itasca County, Minnesota; after Beltsville data (7)[1/]

Depth (Inches)	Horizon	M.E./100 grams soil			Percent B. Sat.	pH	Percent O.C.	Size classes (percent)						
		Ca	Mg	K				Clay	USDA silt	VFS	FS	MS	CS	VCS
3 - 0	A_0	..	..	..	..	6.3	..	..	..	..	..	..	..	..
0 - 2½	A_2	6.9	3.1	<0.1	70	6.6	0.60	14.0	56.9	7.3	11.0	4.2	4.6	2.0
2½ - 6	B_1	12.8	7.1	0.3	83	6.3	0.52	32.5	43.2	7.6	10.4	3.4	2.0	0.9
6 - 19	B_2	15.4	9.3	0.4	91	6.7	0.37	38.2	39.2	7.9	9.2	2.6	2.0	0.9
19 - 31	B_3	16.7	9.4	0.2	98	7.5	0.23	27.0	49.1	8.3	9.3	2.7	2.3	1.3
31 - 39	C_2	20.2	6.6	0.2	100	7.7	0.16	25.8	51.8	8.2	8.6	2.4	2.3	0.9

1/ See page 55 for meanings of abbreviations.

Table 21.--Beltrami silt loam (Gray Wooded) Beltrami County, Minnesota; after Beltsville data (7)[1/]

Depth (Inches)	Horizon	M.E./100 grams soil			Per-cent B. Sat.	pH	Per-cent O.C.	Size classes (percent)						
		Ca	Mg	K				Clay	USDA silt	VFS	FS	MS	CS	VCS
3 - 0	A_0	..	..	..	..	6.6	..	..	..	..	..	..	..	..
0 - 3	A_2	4.0	1.4	<0.1	72	6.4	0.48	8.4	63.2	14.7	8.6	2.2	1.9	1.0
3 - 7	A_3	6.5	2.9	<0.1	77	6.2	0.27	14.8	48.2	18.4	11.2	2.9	2.9	1.6
7 - 12	B_{21}	14.4	6.8	0.3	87	6.6	0.37	28.7	50.0	9.8	7.0	1.9	1.8	0.8
12 - 23	B_{22}	16.3	7.6	0.2	87	6.5	0.36	36.4	54.2	3.9	3.4	1.0	0.8	0.3
23 - 32	B_3	..	..	..	..	7.4	0.18	15.5	83.1	0.6	0.5	0.2	0.1	0.0
32 - 38	C_c	..	..	..	..	7.6	0.14	28.6	68.4	1.2	1.2	0.3	0.2	0.1
42 - 52	C_2	19.6	3.2	<0.1	100	7.8	0.16	12.5	83.8	1.4	1.4	0.4	0.3	0.2

1/ See page 55 for meanings of abbreviations.

Table 22.--Beltrami silt loam (Gray Wooded) Beltrami County, Minnesota; after Beltsville data (7)[1/]

Depth (Inches)	Horizon	M.E./100 grams soil			Per-cent B. Sat.	pH	Per-cent O.C.	Size classes (percent)						
		Ca	Mg	K				Clay	USDA silt	VFS	FS	MS	CS	VCS
2 - 0	A_0	..	..	..	..	5.8	..	..	..	..	..	..	..	..
0 - 6	A_2	2.4	1.0	<0.1	46	5.8	0.32	9.2	34.6	17.4	23.4	7.0	5.0	3.4
6 - 14	B_{21}	8.8	3.9	0.2	71	5.7	0.26	27.3	27.4	14.3	18.8	5.6	4.5	2.1
14 - 22	B_{22}	10.3	4.6	0.2	79	5.6	0.25	27.6	26.2	14.3	19.4	5.8	4.6	2.1
22 - 31	C_{11}	..	..	..	..	7.4	0.27	20.3	38.2	13.9	16.7	4.7	4.2	2.0
31 - 37	C_{12}	21.2	3.1	<0.1	100	7.7	0.14	18.3	40.6	13.1	16.1	5.0	4.6	2.3
37 - 47	C_2	21.2	2.9	<0.1	100	7.8	0.24	16.6	38.6	11.4	20.4	5.7	4.9	2.4

1/ See page 55 for meanings of abbreviations.

Table 23.--Omega loamy fine sand (Brown Podzolic) Pine County, Minnesota; Beltsville data (7)[1/]

Depth (Inches)	Horizon	M.E./100 grams soil			Percent B. Sat.	pH	Percent O.C.	Size classes (percent)						
		Ca	Mg	K				Clay	USDA silt	VFS	FS	MS	CS	VCS
0 - 2½	A_1	3.6	0.7	0.3	31	5.0	3.83	4.2	8.7	3.3	47.8	26.6	8.1	1.3
2½ - 5	A_3	1.5	0.3	0.1	25	5.5	0.88	4.6	8.3	4.0	51.7	25.0	5.9	0.5
5 - 12	B_{21}	0.8	0.2	0.1	21	5.6	0.34	4.3	6.2	3.7	52.4	26.3	6.6	0.5
12 - 18	B_{22}	..	..	..	..	5.6	0.11	3.6	3.9	4.1	55.7	25.9	6.3	0.5
18 - 27	B_3	..	..	..	..	5.8	0.06	3.0	1.0	3.8	67.4	18.4	5.6	0.8
27 - 35	C_{21}	..	..	..	..	5.9	0.05	1.2	0.2	3.3	50.9	35.0	8.7	0.7
35 - 44	C_{22}	0.4	0.1	0.1	40	6.1	0.05	0.9	0.3	7.1	71.5	18.7	1.5	0.0
53 - 60	C_{24}	..	..	..	..	6.3	0.04	0.8	0.0	1.6	42.2	47.8	7.4	0.2

1/ See page 55 for meanings of abbreviations.

Table 24.--Ontonagon clay - Ontonagon County, Michigan; Beltsville data (7)[1/]

Depth (Inches)	Horizon	M.E./100 grams soil			Percent B. Sat.	pH	Percent O.C.	Size classes (percent)						
		Ca	Mg	K				Clay	USDA silt	VFS	FS	MS	CS	VCS
1 - 0	A_0	..	..	..	..	5.4	9.8	..	..	..	..	..	..	..
0 - 6	A_2	2.8	0.7	0.2	36	4.1	1.5	13.4	53.5	8.4	12.5	6.2	3.8	2.2
6 - 8	B_1	2.3	0.7	0.1	31	4.1	0.35	25.6	54.3	7.2	6.9	3.2	1.8	1.0
8 - 24	B_2	7.8	3.3	0.3	53	4.2	0.31	51.5	32.6	4.6	5.8	2.7	1.7	1.1
24 - 36	C_1	14.5	4.1	0.3	100	7.2	0.32	57.5	18.7	3.4	9.0	6.8	3.6	1.0
36+	C_2	14.6	4.3	0.4	100	7.8	0.08	66.5	21.3	3.1	4.5	2.4	1.4	0.8

1/ See page 55 for meanings of abbreviations.