Site Index Curves for European Aspen (*Populus tremula* L.) Growing on Forest Land of Different Soils in Sweden

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Growth data were collected from from 40 European aspen (*Populus tremula* L.) stands growing on eight localities in Sweden. The stands ranged in latitude from 56 to 66°N. The mean age of the stands was 32 years (range, 12–63), the mean stand density 1978 stems ha^{-1} (range, 300–6000), and the mean diameter at breast height (on bark) 17 cm (range, 8–34).

Site index curves were constructed for total age. Curves for H_{40} (dominant height at 40 years total age) were made for total Sweden. Curves fitted for H_{40} total age have another shape than curves presented by other Nordic studies. The curves from the present study have slower growth for young aspens than curves from norwegian and finnish conditions. For 50–70-year-old aspen stands, curves from the present study indicate taller heights than from Nordic studies.

Classified soil types from the stands were grouped into three groups: sandy till (17), light clay (15) and medium clay till (4). As there was only one stand growing in the fine sand group and one stand in the heavy clay till group and two stands in the silty till group, these stands were not presented with growth curves. There were no statistically significant differences in site index between the three soil type groups.

Some recommendations for management of aspen stand are given. Damages caused by moose, fungis and other injuries are discussed as a problem for height yield production and a good timber quality.

Keywords European aspen, *Populus tremula* L., site index curves, total age, soil type, dominant height

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1 Introduction

Aspen has been studied as a potential "producer" of timber of different quality including manufacture of matches cf. Jørgensen (1952); Tikka (1954); Vadla (1987). During recent decades, there has been a general increase in interest in the management of broadleaved trees. This tendency has been evident in the Nordic countries and Europe as well as in Canada and the USA. There are several reasons for the increased interest:

(1) Acid rain, root rot (*Heterobasidion annosum* (Fr.) Bref.) and windbreakage, among other factors, complicate the management of conifer forests. In mixed stands of broadleaved trees and conifers as well as in pure stands of hardwoods these factors are less of problem. Moreover, in some cases, yields can be higher in mixed stands than in pure conifer stands.

(2) The demand for hardwood logs by the pulp industry and sawmills has increased now that a higher percentage of hardwoods can be utilized in recently developed processes. Furthermore, the demand for hardwood logs for use in fine carpentry, e.g. cabinets, and as lumber has increased.

(3) The current emphasis on preserving biodiversity has increased the demand for a larger hardwood component in areas dominated by conifers.

(4) Economic realities make it necessary to rely more and more on natural regeneration. Hardwoods are highly suited for natural-regeneration systems since they can be regenerated by seedfall as well as by suckering and sprouting. The rapid growth of sprouts and suckers offers new ways of solving silvicultural and environmental problems in forestry.

(5) A shelter of aspen reduces both frost risk and competition from weeds for naturally regenerated or planted spruces. A mixed stand of aspens and spruces will produce an early yield when the aspen component is harvested in a single cutting at 40–60 years of age. The remaining spruce stand is clear-cut 20–60 years later cf. Haveraaen (1985). Aspens rapidly colonize open areas and compete with fastgrowing herbs and grasses (Bergmann 1996). This facilitate regeneration of other tree species on the area.

European aspen (*Populus tremula* L.) is distributed throughout the Nordic countries, extending far to the north (lat. 71°N, Alt. 1200 m a.s.l.) and is also found in most parts of Europe and Asia (Blumenthal 1942). Aspen generally grows in small stands (0.1–0.5 ha), most of which consist of a single clone regenerated by suckering. In contrast to the American species quaking aspen (*Populus tremuloides* Michx.), two clones of which were reported to have covered 10.1 and 43.3 ha respectively (cf. Kemperman and Barnes 1976), European aspen clones only cover 1–2 ha at the most. Aspen colonization usually occurs after a forest fire, and the species is very frost tolerant.

Young aspen are often infected by the fungus *Venturia macularis* which causes leaf and shoot blights. Rust on leaves is mostly caused by *Melampsora pinitorqua* Rostr. This pathogen, which alternates between aspen and Scots pine (*Pinus sylvestris* L.) and/or Wild Rosemary (*Ledum palustre* L.), damages leaves, which results in reduced growth. In Scots pine, infections by *M. pinitorqua* cause severe shoot distortion and dieback. Shoestring root rot, caused by *Armillaria mellea* (Vahl.) Quelthe, is a common problem. Species of damaging insects include the Small Poplar Longhorn Beetle (*Saperda populnea* L.), which attacks young aspen suckers; the Goat Moth (*Cossus cossus* L.) and Large Poplar Longhorn Beetle (*Saperda carcharias* L.), which bore in wood of older aspens; and *Orchestes populi* and the White Satin Moth (*Leucoma salicis* L.) which damage leaves and decrease growth. The most serious damage is caused by moose (*Alces alces* Lin.), deer (*Cervus elaphus* Lin.), roedeer (*Capreolus capreolus capreolus* Lin.), hares (*Lepus capensis* Lin, *Lepus timidus* Lin.) and rabbits (*Oryctolagus cuniculus* Pallas) which browse on young trees and gnaw the bark on 10–50-year-old aspens.

In general, the aspen is mixed with other species such as Norway spruce, Scots pine and birches (*Betula pubescens* Ehrh. and *Betula pendula* Roth). Aspen can grow in areas varying widely in climatic conditions and site quality. It performs extremely well on moist, fertile sites, so long as the soil is not a heavy clay. Stoecheler (1960) reported that yields of aspen were highest on soils with 60 % mixed content of light and medium clay and silt soil. On dry, nutrient-poor sites the growth rate is low, the stems tend to be curved, and trees are often bushy. Zehngraff (1947) related aspen yields and rotations to site quality as follows:

- Good sites: Aspen reaches sawlog size at a rotation age of 55 years. Yields of 400 (412) m^3 ha^{-1} or more are attainable.
- Medium sites: The trees produce small logs and pulpwood at a rotation age of 45 years. Estimated maximum yields are about 300 (296) m^3 ha^{-1}.
- Poor sites: Aspen seldom reaches more than pulpwood size at a rotation age of about 30 years. Maximum yields may reach 160 (161) m^3 ha^{-1}, but more often are substantially less than 100 m^3 ha^{-1}. Much of the aspen on poor sites is of no commercial value at the present time.

In a study by Haugberg (1958) the total yield for aspen stands growing under Norwegian conditions, with thinnings every four years until 70 years of age, was presented. The yield was 544 m^3 ha^{-1} for "Bon II" (H_{50} = 22 m) and 456 m^3 ha^{-1} for "Bon III" (H_{50} = 19 m). Petrini (1944) studied aspen stands growing on three experimental plots in southern Sweden (lat. 58°30'N, long. 15°00'E) that had been thinned 5–6 times. He concluded that 60-year-old aspen stands with a density of 300–400 stems per hectare after thinning had a total yield production of 500 m^3 ha^{-1}.

Growth and yield have been studied much more thoroughly in the Canadian species quaking aspen and bigtooth aspen (*Populus grandidentata* Michx.) than in the European aspen. Comparisons between European aspen and quaking aspen have revealed similarities between the two species in growth habit, among others traits (Langhammer and Opdahl 1990). Haugberg (1958) made yield studies and constructed site index curves for European aspen growing under Norwegian conditons. Opdahl (1992) presented a study on European aspen growing in Norway where site index curves for H_{40} at breast height age are given. Vuokila (1977) studied the growth of aspen on good sites for a rotation period of 50 years. In his study, which focussed mainly on volume increment, he concluded that the mean annual increment of aspen stands with a top height of 5–10 m is 12 m^3 ha^{-1} up to the end of the rotation. This is the very highest figure available for a Nordic tree species.

Monserud (1988) challenged the validity of using the site index as a measure of site conditions, especially in mixed uneven-aged forests. But he stated that even if all forest growth modelers realize that soil and climate are major factors influencing tree growth, they also realize the importance of genotype. He presented results from a study where soil characteristics, both chemical and physical properties involved. No combination of soil variables were accounted for anywhere near the same amount of variation as elevation and habitat type.

For expressing the dominant height development over stand age, a large number of growth equations with different numbers of parameters are available (Kiviste,1988. Zeide 1993). Growth equations must fulfil specific requirements cf Peschel (1938):

1. Passing a zeropoint
2. Being increasing
3. Approaching an asymptote which is parallel to the age axis
4. Having an inflection point

When discussing techniques and data sourches for constructing site index curves there are a lot of factors to take account for. Although many different techniques have been used to fit site index curves, most of these techniques can be reviewed from three general equation-development methods (cf Clutter et al. 1983):

1. The guide curve method
2. The difference equation method
3. The parameter prediction method

Data for the development of site index equations are derived from three sources (cf Clutter et al. 1983):

1. Measurement of stand height and age on temporary plots
2. Measurement of height and age over time with monumented trees or plots
3. Reconstruction of height/age development patterns for individual trees through stem analysis techniques

A method for constructing site index curves have been widely used: the guide curve technique (e.g. Bruce 1926; Brickell 1968). A special realisation of the guide curve technique was presented by Tveite (1969). Stem analysis (e.g. Stage 1963;

Carmean 1972) is widely used for data collection. Stem analysis usually results in a more realistic assessment of potential site productivity (Curtis 1964). According to Monserud (1984) this is because (1) more information (a real growth series) is obtained from each sample tree; (2) most stem analysis procedures allow for the estimation of polymorphic height growth patterns; (3) the height of the site trees at index age (i.e. site index) is actually observed for every plot in a stem analysis study, whereas site index in a guide curve study can only be inferred by making assumptions that are often unrealistic (e.g. that all sites are equally sampled at all ages). The kinds of methods used for developing site index curves, together with the types of functions used, are summarized by Hägglund (1981) and Walters and Burkhart (1988).

However, the guide curve technique is sensitive for correlation between site index and stand age in the data (Lappi and Malinen 1994). If this correlation occurs other methods might be used as the difference method (Clutter et al. 1983). In the present study some growth equations expressed for the difference equation method have been tested.

The primary objective of this report is to present site index curves for European aspen growing on different soil types in Sweden. Eight localities ranging in latitude from 56 to 64°N are described. Soil physical types at the eight locations were grouped into three main till categories and site index for aspen reported for them.

2 Material and Methods

Aspen stands were identified at eight localities in Sweden (Fig. 1). Most of the stands had been thinned once prior to the study. Even those that had not been thinned had been cleaned at a young age. Stands accepted for inclusion in the site-index study had to be free from severe moose damage. Forty of the identified stands, ranging in age from 13–63 years, were used in the study (Tables 1 and 2). The mean number of stems per ha was calculated based on the numbers of stems counted in five 100-m^2 plots. In each stand, ten aspens were felled.

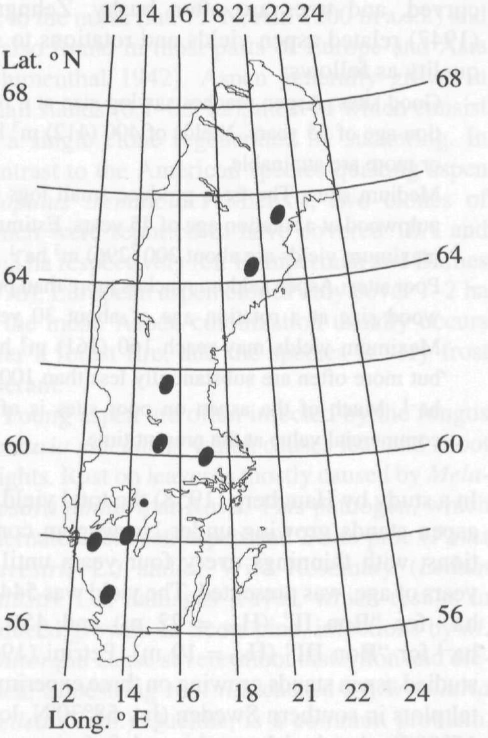

Fig. 1. Map showing the locations of study sites with European aspen (*Populus tremula* L.). The dots represent the location of three permanent aspen plots (Nos. 376, 377 and 378) established in 1916, cf. Table 5.

The mean age at which trees reached breast height (1.3 m) was 2.5 ± 1.6 years (range 1–9 years), with some variation related to the latitude (Table 2). The mean total height of the dominant trees was 16.0 ± 3.3 m (range, 8.2–25.2 m) (Table 2). The tallest aspens occurred in southern and middle Sweden (lat. 56–60°N). The mean total age of the trees examined was 32 ± 11 years (range, 12–63 years) (Table 2). The mean diameter on bark at breast height was 17.1 ± 4.6 cm (range, 8.1–34.0 cm), and the bark thickness averaged 8 ± 3 mm (range, 2–15 mm) (Table 3).

Soil was sampled from ground level down to 30 cm. Samples were taken from six points in the stand. Generally the distance between sampling plots was ten meters. The mean texture for top 30 cm layer was determined. Soil type was classified in the field, following the instructions

Table 1. Main characteristics for stands of European aspen (*Populus tremula* L.) growing at eight localities. 5 stands per location.

Locality	Latitude, N	Longitude, E	Altitude, m	Soil type	Forest type[1)]	Locality	Latitude, N	Longitude, E	Altitude, m	Soil type	Forest type[1)]
1. Älvsbyn (North)						5. Uppland (South)					
1	65°48'	20°32'	135	Light clay till	1	1	60°13'	17°23'	35	Heavy clay till	4
2	65°37'	21°25'	75	Light clay till	1	2	60°13'	17°24'	40	Light clay till	2
3	65°40'	21°24'	135	Sandy till	2	3	60°01'	17°43'	40	Medium clay till	3
4	65°38'	21°24'	150	Sandy till	1	4	59°52'	17°56'	30	Light clay till	2
5	65°41'	20°54'	105	Light clay till	1	5	59°54'	17°53'	20	Medium clay till	2
2. Vindeln (North)						6. Remningstorp (South)					
1	64°11'	19°45'	175	Sandy till	1	1	58°22'	13°59'	125	Light clay till	3
2	64°11'	19°44'	175	Sandy till	1	2	58°23'	14°00'	120	Medium clay till	3
3	64°10'	19°43'	115	Fine sand	1	3	58°22'	14°00'	130	Light clay till	3
4	64°16'	19°41'	225	Silty till	1	4	58°25'	14°08'	125	Sandy till	3
5	64°16'	19°41'	240	Silty till	1	5	58°27'	13°36'	140	Sandy till	3
3. Ljusdal (North)						7. Östad (South)					
1	61°53'	15°24'	375	Sandy till	1	1	57°57'	12°22'	75	Sandy till	4
2	61°53'	15°24'	375	Sandy till	1	2	57°37'	12°22'	80	Sandy till	4
3	61°53'	15°24'	375	Sandy till	1	3	57°58'	12°26'	65	Light clay till	3
4	61°53'	15°24'	375	Sandy till	1	4	57°58'	12°26'	65	Light clay till	3
5	61°53'	15°24'	375	Sandy till	1	5	58°00'	12°27'	70	Light clay till	3
4. Garpenberg (South)						8. Tönnersjöheden (South)					
1	60°13'	16°32'	95	Light clay till	2	1	56°43'	13°08'	95	Sandy till	3
2	60°13'	16°32'	100	Medium clay till	2	2	56°35'	13°05'	40	Light clay till	3
3	60°11'	16°32'	65	Light clay till	3	3	56°43'	13°09'	175	Sandy till	3
4	60°22'	16°03'	85	Light clay till	3	4	56°46'	13°09'	175	Sandy till	3
5	60°22'	16°03'	85	Light clay till	3	5	56°43'	13°08'	95	Sandy till	3

[1)] Hägglund and Lundmark 1982: 1 = Mesic dwarf-shrub; 2 = Mesic grass type; 3 = Mesic dwarf-shrub type with small herbs; 4 = Mesic dwarf-shrub type with tall herbs.

Table 2. Tree height (m), number of stems ha^{-1} and age (years) of European aspen (*Populus tremula* L.).

Locality No. Lat. °N	No. of stands	Height, m		No. of stems ha^{-1}		Age, years		Years to reach breast height (1.3 m)	
		Mean ± 1SD	Min–Max	Mean ± 1SD	Min–Max	Mean ± 1SD	Min–Max	Mean ± 1SD	Min–Max
1. 65–66	5	15.44 ± 2.18	11.2–18.4	2100 ± 412	1700–2800	35 ± 12	18–56	1.9 ± 1.3	1–6
2. 64	5	15.88 ± 1.82	12.7–18.8	900 ± 566	300–1500	39 ± 12	19–63	3.1 ± 1.7	1–8
3. 61	5	14.24 ± 1.47	11.7–17.5	2030 ± 97	1900–2150	30 ± 3	24–37	2.5 ± 1.7	1–9
4. 60	5	14.94 ± 4.43	8.2–22.6	2392 ± 457	1750–2950	27 ± 13	13–52	1.7 ± 0.6	1–3
5. 59–60	5	18.83 ± 3.03	13.4–25.2	1200 ± 464	600–1900	35 ± 7	23–52	2.6 ± 1.5	1–6
6. 58	5	15.70 ± 3.10	9.6–19.9	4280 ± 1836	1400–6000	29 ± 9	15–47	2.6 ± 1.5	1–6
7. 57–58	5	18.23 ± 2.55	13.6–21.7	1320 ± 531	500–1800	34 ± 5	26–45	3.8 ± 1.8	1–9
8. 56	5	15.02 ± 3.56	10.7–22.3	1600 ± 1369	600–4000	31 ± 12	12–61	1.7 ± 1.1	1–5
Total	40	16.04 ± 3.28	8.2–25.2	1978 ± 1293	300–6000	32 ± 11	12–63	2.5 ± 1.6	1–9

Table 3. Diameter at breast height (cm) ob, ub, and bark thickness (mm) for European aspen (*Populus tremula* L.)

Locality No. Lat. °N	No. of stands	DBH, cm ob		DBH, cm ub		Bark thickness, mm	
		Mean ± 1SD	Min–Max	Mean ± 1SD	Min–Max	Mean ± 1SD	Min–Max
1. 65–66	5	14.5 ± 3.1	9.3–21.2	13.6 ± 2.9	8.7–19.6	4.5 ± 1.3	3–8
2. 64	5	17.2 ± 2.0	12.6–21.5	16.1 ± 2.0	11.6–20.3	5.7 ± 1.0	3–8
3. 61	5	14.1 ± 2.7	9.0–22.8	13.3 ± 2.5	8.4–18.8	4.3 ± 1.0	2–6
4. 60	5	14.0 ± 4.4	8.1–22.9	12.7 ± 4.5	6.9–21.6	6.2 ± 2.4	3–15
5. 59–60	5	21.2 ± 5.1	15.2–34.0	19.9 ± 4.9	13.7–32.3	6.6 ± 1.5	5–10
6. 58	5	17.6 ± 4.8	8.1–27.0	16.4 ± 4.5	7.5–25.2	5.7 ± 1.9	3–9
7. 57–58	5	20.4 ± 4.1	11.0–26.1	18.6 ± 3.8	10.3–24.3	6.9 ± 1.8	3–10
8. 56	5	18.9 ± 4.0	10.2–7.8	16.6 ± 3.9	9.2–26.0	6.8 ± 1.2	5–9
Total	40	17.1 ± 4.6	8.1–34.0	16.0 ± 4.4	6.9–32.3	5.9 ± 1.9	2–15

provided by Atterberg in Ekström (1926), and the soils were classified as either sediments or tills. The six individual soil samples were mixed to a general soil sample for the stand. The soil sample (500 g) was then classified based on particle size in the laboratory. The particle-size distribution was determined by a mechanical method with sieves (English and German standard). Soil types were classified in sediments as follows: gravel (20–2 mm), coarse sand (2–0.2 mm), fine sand (0.2–0.02 mm), silt (0.02–0.002 mm), clay (< 0.002 mm), tills; gravel, sandy, fine sandy and silty and organogenic types of soil; moorland peat and moss peat. Although the soil samples contained particles of different size, their type designation was based on the most frequent size, together with one or two prefixes of other less frequent soil types. The clay content was estimated using the hydrometer method. Clay soils were then classified based on their percentage clay as follows: light clay (13–29 %), medium clay (30–40 %), heavy clay (41–60 %) and till clay (13–60 %).

There was only one stand growing on sediments (fine sand), and none of stands were on organogenic soil types. Each stand, mostly 0.1–0.7 ha in size, was divided into five 100 m^2 plots. According to Fries (1964) on each of these plots two dominant (= coarsest tree) trees was chosen for extensive sampling and analysis. These ten trees were then assessed in terms of damage, stem straightness and leader type (single vs dou-

Table 4. Analysis of variance. Test to determine the degree to which "observer" explains variation in the estimated age of European aspen (*Populus tremula* L.)

Source of variation	Degrees of freedom	Sum of squares	Variancae ratios (F)	Prob. > F
Observers[1]	4	317.62500	0.61	0.659
Estimations[2]	1	2.25625	0.02	0.895
Error	154	20 200.46250		
Total	159	20 250.34375		

[1] F 0.05 4.154 = 2.43 (at 5 % level)
[2] F 0.05 1.154 = 3.91 (at 1 % level)

Table 5. Main charactieristics for three stands of European aspen (*Populus tremula* L.) growing on three permanent plots in southern Sweden (lat. 58°42', long. 14°20'E). The plots were established in 1916.

Age, years	Stems ha^{-1}	Diam., cm ub	Height, m
Plot no. 376			
31	960	12.7	14.3
36	691	15.3	16.6
41	604	16.9	17.9
47	415	18.9	19.6
52	356	21.5	20.4
57	283	23.5	21.2
Plot no. 377			
30	903	14.2	15.9
36	761	16.6	18.1
40	643	19.1	19.5
46	493	21.2	21.2
51	442	24.0	22.6
56	398	26.0	23.6
61	366	28.3	24.9
66	351	31.0	25.5
71	298	32.7	26.0
78	206	35.5	26.1
83	206	37.7	27.3
110	201	47.5	30.8
Plot no. 378			
23	1480	10.4	13.2
28	1030	13.4	16.4
33	880	15.2	17.8
39	610	18.0	20.3
44	510	20.7	21.2
49	480	22.7	22.5

ble or broken). The tree also had to be free from root rot which could not be determined until after the tree had been felled. Otherwise a new sample tree was chosen by the remaining trees on the plot. Furthermore, aspens growing in large openings were excluded from consideration.

The chosen trees were then felled and cut as near to the ground as possible in order to measure their height in an easy way. Tree height (m) was measured (Table 2) and diameter at breast height, dbh, (cm) was registered (Table 3). Thereafter, the bark thickness at breast height was measured from two directions. The correlation between bark thickness and diameter is valuable for the input of knowledge about European aspen, especially for Nordic conditions. In Fig. 6 a prediction of regression model including bark thickness and diameter is presented. Detailed descriptions of each stand's characteristics are given in appendices 1 and 2. The stem was then cut into segments for stem analysis. Discs (3–5 cm thick) were cut from the stem at the following heights: 0 (stump height), 50, 130, 200, 300, ... cm. Tree age was determined by counting rings on the discs. Ring width was also measured on the 1.3-m-disc for each tree. A test of the significance of the age determination on disc was made. Five persons examined 16 discs from three sets of trees differing in age, geographical location and growth rate respectively. The discs were mostly from the lower part of the tree, e.g. a high number of rings. The discs were examined twice by each person, but with a week-long interval between examinations. Results of the analysis of variance (ANOVA) are shown in Table 4. As can be seen, neither "observer" nor "estimate" explained a significant amount of variation in the ring counts at the 1% level.

To ensure a "true" height development during the first ten years, young aspens were cut and studied in detail to determine the relation between age and height. At 14 localities (lat. 60–62°N) young aspen stands (5–10 years old) were identified. Ten dominant aspens per stand were then felled and their height and age were registered. In most cases, the age was easy to determine since the leader bud for each year could be detected as a swelling on the stem.

Data from three permanent aspen plots (Nos. 376, 377 and 378) in southern Sweden (lat. 58°42'N, long. 14°22'E, Alt. 151 m a.s.l) have been compared with the results in the present study, cf. Table 5. The aspen start growing in 1885 as suckers on a farmland area and the plot was established by the Department of Forest Yield Research at SLU in 1916, cf. Petrini (1944). The aspen stand was measured and thinned until 1941. Then only plot no. 377 was measured. Last measurement was made in 1995, cf. Table 5.

Difference equation method

Correlation between site index and total age for the aspens was tested. A negative correlation, r = –0.207, between site index and age was found, cf Fig. 2. A weak negative correlation means that the higher stand age the lower site index. As stated by Lappi and Malinen (1994) this may

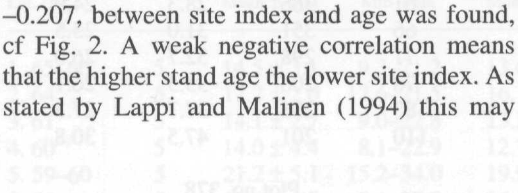

Fig. 2. Correlation between site index (m) and total age (years) for European aspen (*Populus tremula* L.) growing at different localities (lat. 56–64°N). —— SI = 20.194 – 0.061 × Age $R^2 = 0.04$

disturb the statistical analysis when using data from stem analysis. Therefore a method such as the difference equation method was preferred.

Before starting the procedure the data set was divided into three parts: northern Sweden (lat. ≤ 60°N), southern Sweden (lat. > 60°N) and total Sweden, cf. Table 7. Means of height and age were computed and compared. As shown by Table 7, the differences between the parts are small. Then the total data set, 400 aspens, was used in the calculation of parameters for the models.

According to Clutter et al. (1983) the procedure is quite flexible and can be applied with any height/age equation to produce anamorphic or polymorphic curve functions. The initial step is to develop a difference form of the height/age equation to be fitted. The difference form expresses height at remeasurement (H_2) as a function of remeasurement age (A_2), initial measurement age (A_1) and height at initial measurement (H_1). For an analysis of each of the 400 aspens a transformed Chapman-Richard function to difference model expression was used:

$$H_2 = H_1 \times \left(\frac{1 - e^{(B_0 \times A_2)}}{1 - e^{(B_0 \times A_1)}} \right)^{B_1} \tag{1}$$

where

H_1 = height at index age, m
H_2 = height at total age, m
A_1 = age for site index, years
A_2 = tree age, years
B_0, B_1 = parameters

Tree heights and site indices for each of the 400 aspens were computed. Then parameters of the proved difference models were estimated by means of non-linear regression analysis.

The tested functions were:

The "Half saturation function" (Cieszewski and Bella 1989)

$$H_2 = \frac{B_0}{1 + (A_1 / A_2) \times (B_0 / H_1 - 1)} \tag{2}$$

The Hossfield IV function (Peschel 1938)

$$H_2 = \frac{H_1 + D + R}{2 + 4 B_1 \times A_2^{-B_2/(H_1 - D + R)}} \tag{3}$$

Table 6. Percentage bark, %, for different breast height diameter classes, cm, for European aspen (*Populus tremula* L.) growing in northern (lat. 60–66°N) and southern (lat. 56–60°N) Sweden. n = 150 and 250.

	Diameter at breast height, cm (ob) and diameter class												
	8–10	10–12	12–14	14–16	16–18	18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34
Northern Sweden	6.0*	6.0*	6.3*	6.3*	6.4	6.3	-	-	-	-	-	-	-
Southern Sweden	12.5	10.6	7.9	7.9	7.0	6.2	6.8	6.8	6.7	6.1	5.4	4.5	5.4
Total	10.1	8.8	7.0	7.0	6.9	6.2	6.7	6.8	6.7	6.1	5.4	4.5	5.4

* Significant at 5 % level

where

$$D = \left(\frac{B_1}{Asi^{B_2}} \right)$$

$$R = \sqrt{(H_1 - D)^2 + 4B_1 \times H_1 / A_1^{B_2}}$$

Asi = parameter;

The Mitscherlich function (Mitscherlich 1919) or Chapman- Richards function (Richards 1959) derived by Goelz and Burk (1992)

$$H_2 = H_1 \times \left(\frac{1 - e^{(-B_0 \times A_2)}}{1 - e^{(-B_0 \times A_1)}} \right)^{B_4} \qquad (4)$$

where

$$B_0 = \left(B_1 \times \left(\frac{H_1}{A_1} \right)^{A_1} \right)^{B_3}$$

For each aspen, single tree height and age data pairwise was created. All possible pairs both "forwards" and "backwards" were generated according to Goelz and Burk (1992). The total numbers of measurements were 128 890.

The main method was nonlinear regression. When predicting diameter/total age, diameter/dominant height and bark thickness/diameter a linear regression was used. Data were analyzed by analysis of variance and pair-wise comparisons of means using the SAS/STAT system for personal computers (SAS/STAT guide... 1987). For the difference equation method, data were analysed by non-linear regression whereas data for the site index curves were subjected to non-linear regression using the SAS/STAT system for personal computers. A measure of the fit nonlinear regressions was based on the coefficient of determination, $R^2_{est} = 1 - SSE / SS_{total\ (corrected)}$ (Zar 1974).

Table 7. Mean values for height, m and total age, years for European aspen (*Populus tremula* L.) divided in nothern, southern and total Sweden.

	Northern Sweden	Southern Sweden	Total
		No. of aspens	
	150	250	400
Heights, m			
mean	15.19	16.55	16.04
min	11.20	8.20	8.20
max	18.80	25.20	25.20
SD	1.96	3.77	3.28
Age, years			
mean	34.2	31.2	32.5
min	18.0	12.0	12.0
max	63.0	61.0	63.0
SD	10.8	10.1	10.5

3 Results

Estimated parameters for models (1) to (4), Table 8, respectively were computed based on the total data set. All four models behaved well and had a similar performance inside the borders of the data material. No logical performance of asymptotes were obtained for models (2) and (3).

Table 8. Estimated parameters and standard errors of difference equation models (1)–(4).

Model	No. of measurements	Parameter	Parameter estimates	Standard errors of parameters	R^2
(1)	128 890	B_0	0.0235	0.0002	0.979
		B_1	1.1568	0.0036	
(2)	128 890	B_0	94.5876	0.4047	0.978
(3)	128 890	*Asi*	7		0.978
		B_1	693.1702	10.0369	
		B_2	0.9771	0.0026	
(4)	128 890	B_0	0.0047	0.0006	0.979
		B_1	–0.3875	0.0380	
		B_2	0.3591	0.0298	
		B_3	1.1562	0.0036	

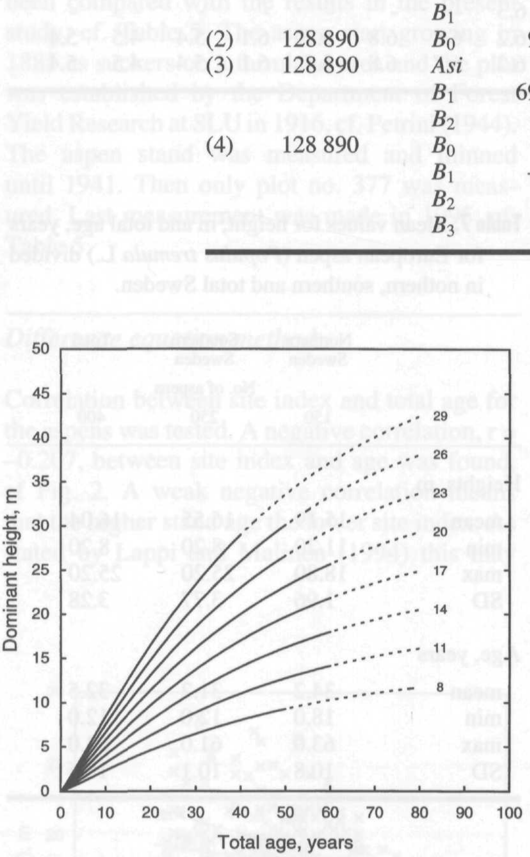

Fig. 3. Site index curves (H_{40}) for European aspen (*Populus tremula* L.) growing at different localities (lat. 56–64°N). n = 40 stands (400 trees).

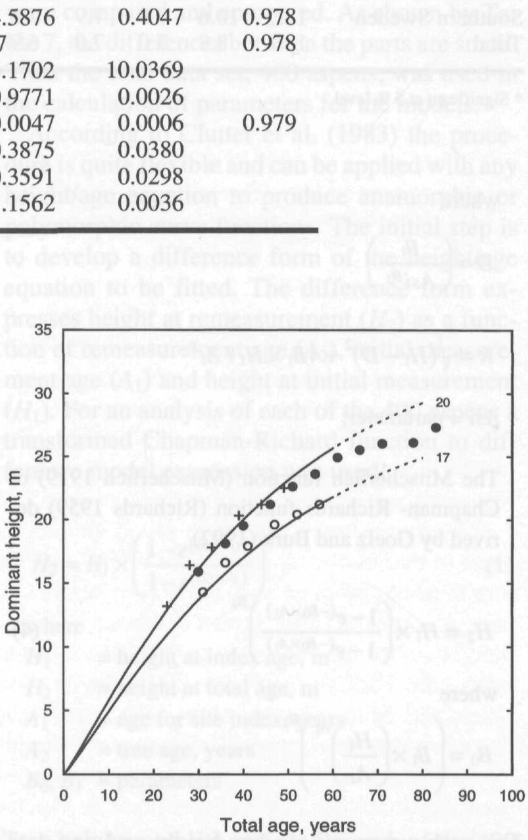

Fig. 4. Site index curves, H_{40} = 17 and 20 m, for European aspen (*Populus tremula* L.). The dots representing mean values from permanent aspen plots, ○ (No. 376), ● (No. 377) and + (No. 379), in southern Sweden (lat. 58°42'N, long. 14°22'E), cf. Table 5.

This problem made it impossible to accept these models as the predicted unrealistic heights for aspens older than 60 years. Models (2) and (3) seemed to be less flexible of application if the trees are young as the aspens in the present study. The fitted curves did not follow a "normal" decrease in height growth by increasing age. In the present study, model (1) is preferred, as this model is simpler to use as only two parameters need to be estimated compared with four parameters for model (4).

Site index curves (H_{40}, total age) for European aspen in Sweden, model (1), are presented in Fig. 3. Since most of the aspens were young, the

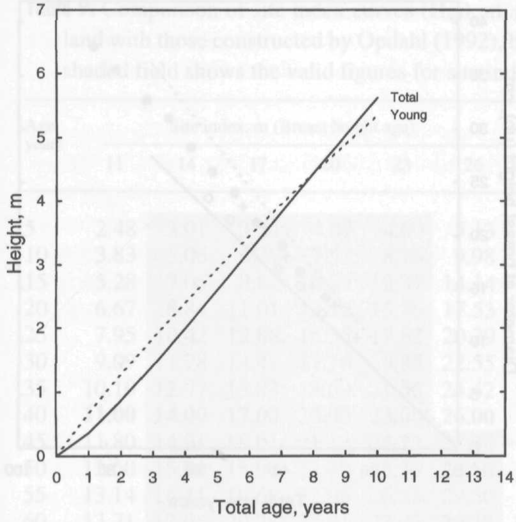

Fig. 5. Relation between height (m) and age (years) for 5–10-year-old suckers (- - -) and 40–60-year-old (––) trees of European aspen (*Populus tremula* L.) growing at different localities (lat. 56–64°N). n = 14 and 40 stands respectively.
–– $H = 21.554 \times (1 - EXP(-0.044 \times Age))^{1.302}$ $R^2 = 0.65$
- - $H = 19.077 \times (1 - EXP(-0.031 \times Age))^{0.963}$ $R^2 = 0.74$

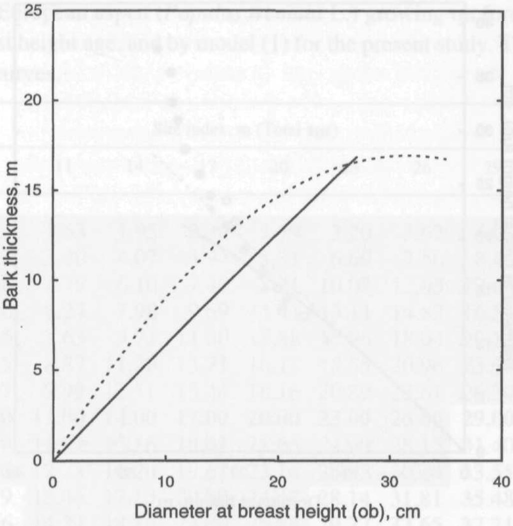

Fig. 6. Relation between bark thickness (mm) and diameter at breast height (cm) for European aspen (*Populus tremula* L.) growing in northern (––) and southern (- - -) Sweden. n = 150 and n = 250.
–– $B = 0.651 \times D - 0.001 \times D^2$ $R^2 = 0.97$
- - - $B = 1.073 \times D - 0.017 \times D^2$ $R^2 = 0.93$

curves are valid only from the beginning to 40 to 60 years age, the exact age limit depending on the H_{40}-level and geographical location. In Fig. 4, the curves for H_{40} = 17 and 20 m are compared with mean heights at different ages from the permanent plots (Nos. 376–378). The aspen heights decrease a little from the H_{40} = 20 m-curve.

Results of the comparison between young suckers and mature material in terms of their temporal patterns of height during the first ten years are shown in Fig. 5. The cumulative height curve for the mature material (function No. 1) is fairly similar to the "young-tree" curve.

The soil profile of each of the stands was analysed and the mineral soil type registered (Table 1). On all locations but one the soil types were represented by till soils. Aspen stand no 3 on locality Vindeln was growing on fine sand. Sandy tills were represented on 17 locations and all stand in Ljusdal were represented by sandy tills. Light clay tills were the soil type on fifteen, medium clay tills on four locations and heavy clay till on one location. Means of site index (H_1) for each aspen growing on a specific soil type was calculated. As the number of stands representing a certain soil type varied, only three soil types were used: light clay till (15), medium clay till (4) and sandy till (17). Site index means (m) for the three tested soil types was: 18.3, 18.8 and 18.0 respectively. A t-test (LSD) showed no statistically significant differences in site index heights between the soil types. A paired analysis of the dependence of site index (m) and soil type including pairs of two stands growing on different soilt type at the same locality and axproximately the same age did not reveal any statistically significant differences.

The fitted curves representing the relation between bark thickness and diameter at breast height (ob) differed in shape between northern and southern Sweden (Fig. 6 and Table 6). At a giv-

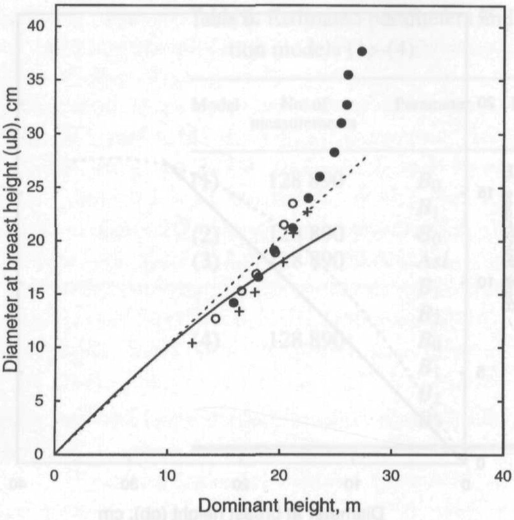

Fig. 7. Relation between diameter at breast height (cm) and height (m) for European aspen (*Populus tremula* L.) growing in northern (—–) and southern (- - -) Sweden. n = 150 and 250 respectively. The dots representing mean values from permanent aspen plots, ○ (No. 376), ● (No. 377) and + (No. 379), in southern Sweden (lat. 58°42'N, long. 14°22'E), cf. Table 5.
—– $D = 1.121 \times Age - 0.011 \times Age^2$ $R^2 = 0.98$
- - - $D = 1.033 \times Age - 0.001 \times Age^2$ $R^2 = 0.97$

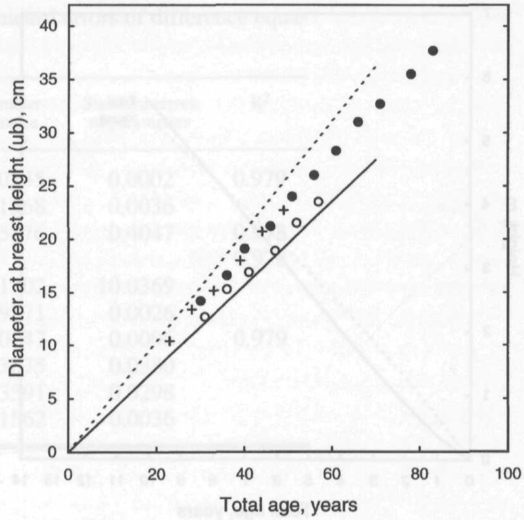

Fig. 8. Relation between diameter at breast height (cm) and age (years) for European aspen (*Populus tremula* L.) growing in northern (—–) and southern (- - -) Sweden. n = 150 and 250 respectively. The dots representing mean values from permanent aspen plots, ○ (No. 376), ● (No. 377) and + (No. 379), in southern Sweden (lat. 58°42'N, long. 14°22'E), cf. Table 5.
—– $D = 0.392 \times Age$ $R^2 = 0.93$
- - - $D = 0.518 \times Age$ $R^2 = 0.94$

en diameter, aspens growing in southern Sweden had a thicker bark than more northerly trees. For aspen growing in the south the curve culminated at a breast height diameter of 30 cm and then dropped at little. For aspen growing in northern Sweden the bark thickness was found to be positively correlated with the breast height diameter. The two curves intersect at 25 cm breast height (ob) and at 15.7 mm bark thickness. There are significant differences in bark percentage means between trees from northern Sweden and those from southern Sweden for the diameter classes 8–10, 10–12 and 12–14 cm ($p < 0.05$, Table 6).

There was a positive, nonlinear association between the dbh (cm) and height (m) of the aspens (Fig. 7). This relationship varied geographically; i.e. trees growing at localities south of lat. 60° had a smaller diameter at a given height compared with trees growing in the north (Fig. 7). Mean values from the permanent plots (Nos. 376–378) had a steeper curve line than the curves from the present study. The relation between dbh and a given total age of aspen trees differed between southern and northern Sweden (Fig. 8). Statistical analyses of the curves did not reveal any significant differences. The mean values from the permanent aspen plot fitted the curves well.

Heights calculated by the deviation method and reported by Opdahl (1992) and those calculated using model (1) in the present study are presented in Table 9. In most cases aspen heights from Opdahl's study were greater for young aspens than those calculated by the present study. Tree heights calculated using the model (1) exceeded those calculated by the deviation method for aspens older than 40 years. However Opdahl's study was based on breast height age and therefore some differences in shape of the compared site curves is due to this phenomenon.

Table 9. Comparison of site index curves (H_{40}), m, for European aspen (*Populus tremula* L.) growing on forest land with those constructed by Opdahl (1992), breast height age, and by model (1) for the present study. The shaded field shows the valid figures for site index curves.

Age years	Site index, m (Breast height age)						Site index, m (Total age)							
	11	14	17	20	23	26	8	11	14	17	20	23	26	29
5	2.48	3.01	3.54	4.07	4.60	5.13	1.11	1.53	1.95	2.36	2.79	3.20	3.62	4.04
10	3.83	5.06	6.29	7.52	8.75	9.98	2.33	3.20	4.07	4.94	5.81	6.69	7.56	8.43
15	5.28	7.05	8.82	10.59	12.37	14.14	3.48	4.79	6.10	7.40	8.71	10.02	12.05	12.63
20	6.67	8.84	11.01	13.19	15.36	17.53	4.56	6.27	7.98	9.69	11.41	13.11	14.83	16.54
25	7.95	10.42	12.88	15.35	17.82	20.29	5.55	7.63	9.71	11.80	13.88	15.96	18.04	20.12
30	9.09	11.78	14.47	17.16	19.85	22.55	6.45	8.87	11.29	13.71	16.13	18.55	20.96	23.38
35	10.10	12.97	15.83	18.69	21.56	24.42	7.27	9.99	12.71	15.44	18.16	20.89	23.61	26.34
40	**11.00**	**14.00**	**17.00**	**20.00**	**23.00**	**26.00**	**8.00**	**11.00**	**14.00**	**17.00**	**20.00**	**23.00**	**26.00**	**29.00**
45	11.80	14.91	18.01	21.12	24.23	27.34	8.79	11.91	15.16	18.41	21.65	24.90	28.15	31.40
50	12.50	15.70	18.90	22.10	25.30	28.50	9.26	12.73	16.20	19.67	23.14	26.93	30.44	33.55
55	13.14	16.41	19.68	22.96	26.23	29.50	9.79	13.46	17.13	20.80	24.47	28.14	31.81	35.48
60	13.71	17.04	20.38	23.71	27.05	30.38	10.26	14.24	18.12	22.00	25.88	29.77	33.65	37.21
65	14.22	17.61	21.00	24.38	27.77	31.16	10.69	14.70	18.71	22.72	26.73	30.73	34.74	38.75
70	14.68	18.12	21.55	24.99	28.42	31.85	11.07	15.22	19.37	23.53	27.68	31.83	35.98	40.13
75	15.11	18.58	22.05	25.53	29.00	32.47	11.41	15.69	19.97	24.25	28.53	32.81	37.09	41.37
80	15.49	19.00	22.51	26.01	29.52	33.03	11.72	16.11	20.50	24.90	29.29	33.68	38.07	42.27

4 Discussion

In the present study five aspen clones were measured per locality. Table 1 reveals that clones grew on only one soil type only at Ljusdal and that forest type in which clone grew were uniform at four of eight locations. When calculating dominant-height-curves, all the measured trees were used. In common practice, the presented site index curves are means for many clones. Due to clonal variation, no single clone can be used to obtain an accurate estimate of aspen site index. Zahner and Grawford (1965) studied the clonal concept for North American aspen site relations.They concluded that the genetic structure of aspen stands, in which trees develop in clones composed of genotypically identical stems, can explain more of the variation in performance on a given site than soil type can. Dominant trees from the same clone showed similar height-age relations, which means that it may only be necessary to measure a few aspens per clone. However, the variation in height-age relations between clones is great; therefore, at least three clones must be measured to obtain a satisfactory estimate of site quality. In the present study this postulate was fulfilled.

Prior to the measurements, some of the stands had been thinned once. In a study such as this, it is important that height growth, especially for the tallest trees, has not been influenced by thinning operations, for example, by decreasing either the mean height growth or the "potential" height. In a study connected with a large trial including many parts of Europe and many tree species, Braathe (1957) concluded that thinning generally has neutral or negative effects on the "true" height growth of broadleaved trees. Thinning has a stronger influence on the height-diameter relation in broadleaved stands than in conifer stands.

In the present study site index curves are presented for total age. Since the year during which the stands had been established was not known and since the first 10–15 years of seedling/sapling development were compared in a separate study, cf. Fig. 4, the height-age relation determined should be reliable. In practice, not enough attention is given to the period between seeding or planting and the time at which breast height is reached for aspens growing on forest land. Reduced height growth is common at this stage, owing to browsing and frost injury to leaders, among other causes. In the present material the time needed for the aspens to reach breast height (1.3 m) was the same, i.e. 2.5 years (range 1–9 years) for stands growing in northern (> 60°N) and southern (< 60°N) Sweden (Table 2).

The present investigation was based primarily on trees with an H_{40} (at total age) of 8–29 m, with most of the studied trees having an H_{40} between 11 and 26 m. Since most of the trees are young, i.e. 40–70 years old, the site index curve cannot be used reliably for predicting heights at 90–100 years of age. However, most stands of the type covered in this study will have been clear-felled prior to reaching 60–80 years of age. Thus in practice, extrapolation would rarely be necessary, especially for stands in southern Sweden. In older Swedish studies made by Schotte (1917), aspens growing on a site assigned the name "Bon I" were 13 m high at 23 years old, and were 16, 22 and 26 m at 30, 53 and 85 years respectively. These heights correspond to the present studies: H_{40} = 20, 20, 17–20 and 17 m respectively. Schotte's curve for "Bon I" flattened out more than for H_{40} = 20 m in the present study.

Site index curves (H_{40}) based on total age for aspens in the present study were compared with corresponding curves based on breast height age constructed by Opdahl (1992). In Table 9 site index for five-year intervals estimated by Opdahl's curve and model (1) from the present study are shown. The compared curves have different shapes mainly as they are constructed by different ages (breast height versus total age). Thus, compared with Opdahl's curves, the curves indicate that young aspens grow more slowly but reach greater heights at 50–70 years of age. Differences in predicted height were 2–14 dm for young aspens and 2–20 dm for old ones. The present site index curves are only valid for aspen material upon which the analyses were based. The temporal pattern of height growth of young aspens (suckers) is shown in Fig. 5, where the heights for aspens estimated in young stands as well as heights for all examined trees were used to construct the site index curves. Curves in Opdahl's study indicate that young trees reach 3.8–10.0 m within their first 10 years. This rate is higher than that reported in other studies (approximately 5 m), cf. Reim (1930), Haveraaen (1985) and in the present study (2.3–8.4 m). The lower growth rate in the present study might be due to damage caused to young trees by browsing moose and red deer. In general, numbers of moose and red deer have been much higher in Sweden than in Norway and Finland. Foresters have noted that the growth of young suckers browsed at 1–2 m height remains retarded for some years, whereupon they either show a spurt in growth or slowly die.

In Norway, Haugberg (1958) presented site index curves (H_{50}) for aspen which were later complemented with data by Børset and Haveraaen (1960). A comparison between the present site index curves and those published by Haugberg has been made. The Norwegian curves were classified into four groups: Bon I, II, III and IV. These classes are comparable to H_{50} = 24, 22, 19 and 16 m. Heights at 40 years of age according to the curves are 21, 19, 16 and 13 m respectively. The curves obtained in the present study differ in shape from the Norwegian curves. Like Opdahl's curves, the Norwegian site-index curves show a greater drop at 60 years of age compared with the present curves. But for aspens younger than 40 years of age, the heights representing site-index classes ("Bon") for the Norwegian curves tend to exceed those indicated by the present site index curves.

Blumenthal (1942) presented height curves for aspen under different site conditions in Finland, referring to Kurdiani (1934). Aspens growing on "Bon I" had a height of 21.2 m at 40 years of age, and heights of 24, 26 and 29 m at 50, 60 and 70 years of age respectively. For "Bon III" corresponding heights were 15.0, 18.5, 20.6 and 23.0 m. Heights for the poorest site, "Bon V", were 10.7, 12.1 and 13.5 m for 40, 50 and 60 years of age respectively. Compared with the site index curves in the present study, aspen growing on "Bon I" are 1 m higher at 40 years compared with aspen of the same age on the H_{40} = 20 m site, but at 50, 60 and 70 years the H_{40} = 23 m curve is similar to "Bon I". For "Bon III" 40 to 70-year-old aspens are taller compared with trees on H_{40} = 14 m, but lower compared with trees on H_{40} = 17 m. For the poorest site, "Bon V", the curve from Kurdiani's study flattened out from H_{40} = 11 m for 40-year-old aspens to below H_{40} = 8 m for 60-year-old aspens. This indicates that the growth rate of aspen growing on poor sites varies depending on the incidence and severity of rot disease and other types of damage.

Site index curves (H_{30}) for quaking aspen presented by Graham et. al. (1963) were compared with the present curves. The quaking aspens grew slower at higher ages than aspens in the present study. The authors stated that the aspen curves flattened out to various degrees for trees greater than 50 years of age, depending on the environmental conditions. An improvement in conditions will even enhance the growth of old (> 50 years old) trees.

Young aspen suckers grow very fast during the first 5–10 years, cf. Fig. 5. Reim (1930) reported a height growth rate of 1 m per year, and a 3-year-old sucker was 2.8 m high. Most young aspens are suckers. Aspen seedlings are rare since the site conditions (dryness, shade and weed competition) combined with the strong competition from surrounding vegetation and damage caused by insects and voles result in extremely high mortality. Haveraaen (1985) reported that the heights of birch sprouts (*Betula pendula* Roth and *Betula pubescens* Ehrh.) and seedlings of birch were 2.2 and 1.0 m at five years of age and 5.0 and 2.8 m at ten years of age respectively. Mean heights for five- and ten-year-old aspen suckers in the present study were 3.0 and 5.4 m respectively. Since young aspen suckers grow rapidly, after one or two years they overtop most of the surrounding vegetation, such as grasses and herbs, and most of the understory of hardwood and conifer species.

On fertile sites, such as those on former farmland, the potential for rapid height and volume growth is great. On most such sites, however, the incidences of disease and distortion caused by wind increase substantially with age. Thus, most aspens and aspen stands are clear-felled when they are 60–80 years old. Clear-felling at this age is most profitable in stands with a low incidence of injuries. If good timber quality is a high priority, aspens should be cut when they are 40–50 years old. On the other hand, Monserud (1988) stated that in his study of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. glauca) and soil variables, only 16 percent of the variation in site index was explained by soil properties.

In the present study the mean of site index for aspen growing on light clay till, medium clay till and sandy till soils did not differ in a statistically significant way. The aspen stands studied in the present study grew on sites where the conditions for aspen growth were good. Mostly clones of aspens are growing on small areas, 0.3–1.0 ha, and utilize the micro sites well. Results presented by Fralish (1972) indicate that aspen site index is strongly influenced by soil texture. As the percentage of silt increased (5–90 %) the average site index (age 50) increased (69–85 feet). As the sand content decreased (95–5 %) the site index increased. However, the influence of site factors other than soil texture, e.g. water table depth, will cause ranges to overlap. A water table depth of 90 to 240 cm is conductive to aspen growth. Water tables deeper than 240 cm will have little effect on growth since few roots penetrate below that depth. Most of the poorer forest types are more common in northern Sweden than in southern parts of the country, cf. Appendix 1. These findings are supported by Walters et. al. (1990) who studied the relationship between aspen site index and synecology coordinates (moisture, nutrient, heat and light). They found that site index was significantly related to both nutrient status and moisture status. However, the most northern aspen stands studied in the present study grew on fertile soils.

Observations and experimental results indicate that with increasing age, growth decreases, sometimes sharply, in aspen stands on sediments of heavy clay soils, whereas damage frequency increases, especially on former farmland. There are many theories to explain the increased damage and slower growth: Holmsgaard (1955) and Bavngaard (1962) found that with age, spruce became increasingly sensitive to a dry period in June–July, which retarded its growth. Holstener-Jørgensen (1973) reported that dryness increased owing to the high content of clay mud in the till clay soils. Water availability in a soil is negatively related to its clay content. On the other hand, it is not possible to drain heavy clay areas by ditching if the water content is too high; thus seedling roots can suffer from anoxia under such conditions (Holstener-Jørgensen and Kjersgård 1982). When calculating site index values the slower growth on sediments of heavy clay soils should be taken into account. In Sweden such soils are most frequent in southern parts of the country (lat. 57–59°N).

A practical implication of the results from the present study and findings in other reports is that aspen stands grow fast on fertile sites. A dense stand on a fertile site, especially farmland, must be thinned heavier and earlier as compared with a wider stand. The risk for root rot is increased by an early, intensive thinning. Many of the aspens in the residual stand will, subsequently, become infected via contact with roots from infected stumps and trees in the neighbourhood (Paludan 1966; Stenlid 1985). The presented site index curves, (Fig. 3), indicate that on sites $H_{40} <$ 14 m, aspen will grow too slowly. These sites must be avoided if quality timber and fast growth are important for the forest owner. Even sites with sediments of heavy clay soils must be avoided since the water supply is too low for the fast-growing aspens. On poor sandy till soils, most of which support Scots pine stands, aspens generally grow slowly, develop bent stems and contain a high percentage of rot.

Aspen suckers are very sensitive to fungal infections that spread from the mature tree and its roots. Basham (1982) reported that the percentage of infected suckers was higher on a scarified soil than on a control (unscarified) soil. In most cases of infection, the stems had been damaged by the scarifier. Since aspen is highly susceptible to attack by certain fungi, certain preventative silvicultural treatments should be applied, (cf. Eklund and Wennmark 1925). For example, aspen stands must be protected against grazing by cattle, sheep and horses. Furthermore, precautionary measures must be taken when the stands are thinned, especially when skidding the pulpwood and timber. If aspens are to grow rapidly over the long term, infections must be minimized and the stands must be thinned in a way that will not adversely affect growth. Walters et. al. (1982) studied the effects of partial cutting on diseases and mortality in quaking aspen stands. They concluded that in the 5–7-year period after logging, 45 % of stems the remaining stems were infected with cankers, and aspen mortality averaged 20 %. This mortality was 20 times the rate in control plots (not harvested). Thus harvesting methods must be greatly improved to reduce the amount of harvest-associataed stem and root wounding. Generally aspen only grows rapidly on good sites, where the rot frequency is generally low. However, there are highly significant differences among quaking aspen clones in terms of percent decay, volume of decay and major types of rot present (Wall 1971).

Browsing moose and red deer cause injuries that can act as infection courts for the spores of fungal pathogens, which can also result in infected suckers. Krebill (1972) studied the degree of mortality of quaking aspen browsed by elk (*Cervus canadensis* Nelsoni) and moose. He reported that bark wounds caused 90 % of the mortality among studied aspens (n = 4 016), while 27 % of the 90 % were killed by stem-boring insects and 25 % by Scoty bark canker. Only 1% were killed by rot. Older trees died of windbreakage or windthrow, probably as a result of bark wounds at an earlier stage.To manage aspen stands for the production of high quality timber these types of damage must be avoided. In practise, this is very difficult, especially on forest land. Most stands must be fenced off, which is possible on former farmland but it is expensive. The aspen tree is sensitive to browsing for as long as the bark is smooth and green, i.e. for 30–50 years.

The relation between diameter at breast height and bark thickness for aspens growing in southern Sweden is shown in Fig. 6. The curve has the same shape as that reported by Eklund and Wennmark (1925) for aspen growing in middle Sweden (lat. 59–60°N long. 10–11°E). In a study by Børset (1954) on aspen growing under Norwegian conditions (lat. 58–63°N long. 5–12°E) a curve similar to that shown in Fig. 6 for northern Sweden was presented. However, for a given diameter, bark thickness is greater for the Norwegian curve than for the present curve. Finnish curves (Blumenthal 1942) relating diameter to bark thickness for aspen growing at lat. 60–70°N, long. 21–32°E are much steeper than the three above-mentioned curves. In a study of aspen logs by Børset (1952) the mean bark thickness at breast height for 1 072 butt logs was 20 mm, and the mean bark percentage was 7.9 %. The aspen logs were cut in southern Norway (lat. 58–61°N, long. 5–12°E). The bark percentage figures for different diameter classes in this study are similar to those presented in the study mentioned above by Børset (1954). The diameter classes 8–10, 10–12 and 12–14 cm differ significantly in terms of bark percentages between northern and southern Sweden. The bark percentage was much lower for northern Sweden, especially for thin stems. At breast height the bark on northern aspens was smoother than that on southern growing aspens, which mostly have a thick, rough bark.

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Appendix 1. Height, age and density for each stand.

Locality No.	Height, m		Total age, years		No. of stems ha^{-1}
	Mean ± SD	Min–Max	Mean ± SD	Min–Max	
1. Älvsbyn (North)					
1	17.19 ± 0.62	16.4–18.4	55 ± 1	53–56	2000
2	14.69 ± 1.52	11.9–16.3	22 ± 2	18–26	2800
3	16.19 ± 1.62	13.9–17.8	39 ± 2	37–44	1700
4	16.96 ± 1.09	14.5–18.3	34 ± 2	31–37	2000
5	12.17 ± 0.59	11.2–13.4	23 ± 2	20–27	2000
Total	15.44 ± 2.18	11.2–18.4	35 ± 12	18–56	2100 ± 412
2. Vindeln (North)					
1	13.75 ± 0.81	12.7–15.0	21 ± 1	19–22	700
2	18.37 ± 0.43	17.5–18.8	52 ± 1	51–54	1500
3	16.15 ± 1.46	13.5–17.9	48 ± 11	31–63	1500
4	15.55 ± 0.94	13.9–17.1	36 ± 3	31–41	300
5	15.59 ± 1.42	13.1–17.0	36 ± 4	30–42	500
Total	15.88 ± 1.82	12.7–18.8	39 ± 12	19–63	900 ± 566
3. Ljusdal (North)					
1	13.80 ± 1.28	11.9–15.6	27 ± 4	24–37	2000
2	13.38 ± 1.55	11.7–17.0	29 ± 2	24–31	1900
3	14.99 ± 0.87	13.8–16.8	30 ± 2	28–34	2100
4	13.49 ± 0.69	12.7–14.6	30 ± 2	27–33	2000
5	15.53 ± 1.52	12.5–17.5	31 ± 2	28–34	2150
Total	14.24 ± 1.47	11.7–17.5	30 ± 3	24–37	2030 ± 97
4. Garpenberg (South)					
1	12.05 ± 1.00	9.4–13.0	15 ± 1	13–17	2950
2	11.03 ± 1.99	8.2–13.7	16 ± 1	14–17	2700
3	11.45 ± 0.51	10.7–12.3	19 ± 2	17–23	2600
4	18.80 ± 1.05	17.0–20.1	39 ± 6	33–52	1960
5	21.40 ± 1.00	19.1–22.6	46 ± 2	43–49	1750
Total	15.10 ± 4.31	9.4–22.6	27 ± 13	13–52	2392 ± 457
5. Uppland (South)					
1	23.58 ± 0.85	22.6–25.2	39 ± 3	34–43	600
2	16.91 ± 0.99	15.5–18.5	31 ± 2	27–34	1100
3	16.18 ± 1.59	13.4–18.4	28 ± 3	23–33	1200
4	16.90 ± 1.06	15.6–18.6	32 ± 5	26–42	1200
5	20.58 ± 0.43	20.0–21.3	45 ± 4	39–52	1900
Total	18.83 ± 3.03	13.4–25.2	35 ± 7	23–52	1200 ± 464
6. Remningstorp (South)					
1	18.93 ± 0.57	18.2–19.9	38 ± 3	34–44	3600
2	13.53 ± 1.40	11.1–15.7	22 ± 2	19–25	5400
3	16.70 ± 1.03	15.2–18.5	32 ± 2	29–36	5000
4	11.34 ± 1.26	9.6–13.0	17 ± 2	15–19	6000
5	18.02 ± 1.55	14.9–19.6	34 ± 6	27–47	1400
Total	15.70 ± 3.10	9.6–19.9	29 ± 9	15–47	4280 ± 1836

Appendix 1 continued.

Locality No.	Height, m		Total age, years		No. of stems ha^{-1}
	Mean ± SD	Min–Max	Mean ± SD	Min–Max	
7. Östad (South)					
1	20.45 ± 1.42	17.0–21.7	40 ± 4	31–45	1800
2	18.41 ± 1.34	15.7–19.6	30 ± 4	26–38	1700
3	17.83 ± 0.63	17.0–19.0	35 ± 2	32–38	1100
4	20.40 ± 0.72	19.0–21.5	36 ± 3	30–40	1500
5	14.05 ± 0.62	13.6–15.7	31 ± 3	26–35	500
Total	18.23 ± 2.55	13.6–21.7	34 ± 5	26–45	1320 ± 531
8. Tönnersjöheden (South)					
1	15.38 ± 0.99	14.1–17.1	31 ± 2	27–34	1200
2	12.56 ± 0.66	11.5–13.8	27 ± 3	22–31	4000
3	11.77 ± 0.60	10.7–12.7	17 ± 4	12–23	1300
4	21.46 ± 0.70	20.3–22.3	51 ± 7	43–61	600
5	13.96 ± 0.87	12.4–15.1	30 ± 2	28–33	900
Total	15.03 ± 3.56	10.7–22.3	31 ± 12	12–61	1600 ± 1369

Appendix 2. Diameter and bark thickness for each stand.

Locality No.	Diameter at breast height, cm				Bark thickness, mm	
	On bark		Under bark			
	Mean ± SD	Min–Max	Mean ± SD	Min–Max	Mean ± SD	Min–Max
1. Älvsbyn (North)						
1	17.5 ± 2.1	14.3–20.6	16.5 ± 2.0	13.5–19.6	4.8 ± 1.2	3–7
2	13.0 ± 1.6	10.7–15.7	12.3 ± 1.5	10.1–14.7	3.9 ± 0.7	3–5
3	17.3 ± 2.7	12.4–21.2	16.1 ± 2.4	11.6–19.6	6.2 ± 1.3	4–8
4	12.9 ± 1.6	11.4–15.5	12.2 ± 1.5	10.6–14.5	3.8 ± 0.6	3–5
5	11.9 ± 2.4	9.3–15.8	11.2 ± 2.3	8.7–15.0	3.7 ± 0.8	3–5
Total	14.5 ± 3.1	9.3–21.2	13.6 ± 2.9	8.7–19.6	4.5 ± 1.3	3–8
2. Vindeln (North)						
1	15.6 ± 1.9	12.6–19.0	14.5 ± 1.9	11.6–17.6	5.6 ± 0.8	5–7
2	17.0 ± 1.8	14.6–20.2	15.9 ± 1.8	13.5–18.8	5.6 ± 0.7	5–7
3	17.2 ± 1.3	15.4–19.2	16.2 ± 1.3	14.6–18.0	5.1 ± 1.0	3–6
4	18.4 ± 2.3	14.0–21.5	17.3 ± 2.2	13.0–20.3	5.4 ± 0.5	5–6
5	18.0 ± 2.0	14.6–21.0	16.6 ± 1.9	13.4–19.8	6.7 ± 0.9	5–8
Total	17.2 ± 2.0	12.6–21.5	16.1 ± 2.0	11.6–20.3	5.7 ± 1.0	3–8

Appendix 2 continued.

Locality No.	Diameter at breast height, cm				Bark thickness, mm	
	On bark		Under bark			
	Mean ± SD	Min–Max	Mean ± SD	Min–Max	Mean ± SD	Min–Max
3. Ljusdal (North)						
1	14.8 ± 3.3	9.8–20.0	13.9 ± 3.1	9.2–18.8	4.6 ± 1.2	3–6
2	14.0 ± 2.1	10.0–17.0	13.1 ± 2.0	9.6–16.0	4.5 ± 1.2	2–6
3	15.1 ± 2.8	12.1–19.8	14.2 ± 2.7	11.3–18.8	4.4 ± 0.5	4–5
4	11.9 ± 1.5	9.0–14.0	11.2 ± 1.4	8.4–13.0	3.8 ± 1.0	3–6
5	14.9 ± 2.3	10.1–18.4	14.0 ± 2.3	9.5–17.4	4.1 ± 0.7	3–5
Total	14.1 ± 2.7	9.0–20.0	13.3 ± 2.5	8.4–18.8	4.3 ± 1.0	2–6
4. Garpenberg (South)						
1	10.9 ± 0.9	8.9–12.2	9.5 ± 1.0	7.4–11.0	6.4 ± 1.0	5–7
2	9.7 ± 1.8	8.1–12.8	8.4 ± 1.6	6.9–11.1	6.7 ± 2.1	3–9
3	12.2 ± 3.0	8.7–17.6	10.5 ± 2.5	7.6–15.4	8.8 ± 3.4	3–15
4	18.3 ± 2.8	14.0–22.8	17.3 ± 2.7	13.2–21.6	5.3 ± 0.8	4–7
5	18.4 ± 2.7	12.8–22.0	17.6 ± 2.6	12.2–21.0	4.0 ± 0.8	3–5
Total	13.9 ± 4.4	8.1–22.8	12.7 ± 4.5	6.9–21.6	6.2 ± 2.4	3–15
5. Uppland (South)						
1	29.7 ± 3.4	23.5–34.0	28.1 ± 3.3	22.3–32.3	7.6 ± 1.5	6–10
2	17.9 ± 1.5	15.3–20.8	16.6 ± 1.6	13.7–19.4	6.5 ± 1.3	5–9
3	18.4 ± 2.0	15.6–22.1	17.3 ± 2.0	14.6–21.1	5.3 ± 0.5	5–6
4	18.6 ± 2.5	15.2–23.7	17.4 ± 2.3	14.2–21.9	6.0 ± 1.2	5–9
5	21.4 ± 2.9	17.3–26.2	19.9 ± 2.7	16.1–24.4	7.6 ± 1.4	6–10
Total	21.2 ± 5.1	15.2–34.0	19.9 ± 4.9	13.7–32.3	6.6 ± 1.5	5–10
6. Remningstorp (South)						
1	22.7 ± 1.8	19.7–25.7	21.1 ± 1.7	18.1–24.1	7.9 ± 0.7	7–9
2	14.9 ± 1.6	12.7–17.9	14.1 ± 1.5	11.9–16.9	4.3 ± 0.7	3–5
3	16.9 ± 1.6	15.1–19.9	15.9 ± 1.4	14.3–18.5	5.3 ± 0.9	4–7
4	11.1 ± 1.6	8.1–12.8	10.3 ± 1.5	7.5–12.0	3.6 ± 0.5	3–4
5	22.2 ± 2.9	17.9–27.0	20.7 ± 2.7	16.7–25.2	7.5 ± 1.2	6–9
Total	17.6 ± 4.8	8.1–27.0	16.4 ± 4.5	7.5–25.2	5.7 ± 1.9	3–9
7. Östad (South)						
1	20.5 ± 2.9	16.9–25.3	19.1 ± 2.6	15.9–23.3	7.0 ± 1.6	5–10
2	23.0 ± 1.5	20.8–25.3	21.3 ± 1.4	19.2–23.5	8.5 ± 0.5	8–9
3	21.8 ± 1.9	19.7–26.1	20.2 ± 1.8	18.3–24.3	7.8 ± 0.6	7–9
4	21.5 ± 1.7	18.6–24.6	20.0 ± 1.6	17.4–23.0	7.5 ± 0.7	6–8
5	13.1 ± 2.4	11.0–19.4	12.4 ± 2.3	10.3–18.4	3.9 ± 0.7	3–5
Total	20.0 ± 4.1	11.0–26.1	18.6 ± 3.8	10.3–24.3	6.9 ± 1.8	3–10
8. Tönnersjöheden (South)						
1	17.2 ± 2.7	13.4–21.4	15.9 ± 2.5	12.4–19.8	6.5 ± 0.8	5–8
2	20.1 ± 5.3	14.4–27.8	18.7 ± 5.0	13.2–26.0	7.1 ± 1.5	5–9
3	15.3 ± 3.0	10.2–20.2	14.0 ± 2.9	9.2–19.2	6.6 ± 1.4	5–9
4	21.2 ± 3.2	15.9–25.9	19.7 ± 3.2	14.7–24.7	7.0 ± 1.1	6–9
5	16.3 ± 2.6	12.0–21.0	14.9 ± 2.4	10.8–19.2	6.7 ± 1.3	5–9
Total	18.0 ± 4.0	10.2–27.8	16.6 ± 3.9	9.2–26.0	6.8 ± 1.2	5–9