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Yield Potential of *Quercus robur* Stands in Finland

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Yield potential of common oak (*Quercus robur* L.) stands in Finland was examined by estimating the site index value with a Swedish model of a sample of 23 existing stands in southern Finland, and studying its correlation with site fertility and geographical location. Stand structure and yield parameters were compared with those suggested by the Swedish management regimes to assess their condition and potential for quality oak production. External wood quality and sawlog volume were examined in sample tree data. The study stands scored high site index values on the reference site index curves from southern Sweden. The most fertile sites showed an average site index value of $H_{100} = 28–30$ m, and the common *Oxalis–Myrtillus* type $H_{100} = 24–26$ m. In the absence of thinning and pruning, the external quality of the trees was poor. Defects had reduced the sawlog proportion on average by 40% from the estimated maximum allowed by tree dimensions. *Key words: growth, management, oak, silviculture, stand structure, wood quality.*

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INTRODUCTION

Indigenous common oak (*Quercus robur* L.) grows as solitary trees, tree groups and small pure stands on a narrow south-western coastal strip in Finland (Fig. 1), probably limited by both ecological factors and human exploitation (Ollinmaa 1952, Rainio 1977, Solantie 1983, Hämet-Ahti et al. 1992). It has thrived on exceptionally favourable sites even in Tornio (Ollinmaa 1952), and Rovaniemi, 700 km further north than its natural distribution. Its current role in forestry is negligible. However, interest in the cultivation of oak and other rare broadleaved species rose during the 1990s along with the initiatives for promoting ecological sustainability and forest amenity, afforestation of agricultural fields and intensified utilization of valuable timber resources as alternatives for intensive pulpwood production. Oak is a valuable species both as a habitat for rare or threatened species (Alanen 1988, Alapassi & Alanen 1988, Annila 1998) and as a timber resource (Riikilä 1987, Kiuru 1991*c*, Louna & Valkonen 1995). Almost all oak wood consumed in Finland (equivalent of 33 000 $m^3\ yr^{-1}$ sawlogs in the year 1993; Louna & Valkonen 1995) is imported. The existing planted stands comprise an area of less than 1000 ha and the scattered natural stands could by no means serve as a significant resource base.

However, cultivated and well-managed oak stands could have the potential to produce valuable timber in Finland, and not only within its constrained natural distribution area (Ollinmaa 1952). Research results and practical experience on the site requirements, productivity and effects of management practices are still virtually non-existent compared with pine, spruce and birch in Finland. Management objectives and guidelines have been presented (Rainio 1986, Riikilä 1987, Kiuru 1991*a*,*b*, Antikainen 1992, Tyystjärvi 1994, Valkonen et al. 1995, Jalopuumetsät 1997), but they have been based mainly on Swedish models (Carbonnier 1975, Almgren et al. 1984, Stål 1986, Anon. 1991, Eriksson 1991). Because a reliable reference point is not available, forest managers still have difficulty in deciding what to aim for and what to expect from an oak plantation in Finland.

The research results on oak productivity with the closest geographical location and probably the greatest relevance for Finland are those by Carbonnier (1975). Based on an empirical data set of 29 stands in southern Sweden, he constructed site index curves and growth models for oak in Sweden. Using the models for simulation, he constructed yield tables for the production of valuable large-dimensioned oak timber with two alternative management regimes. Alternative A represented a traditional standard programme with numerous thinnings at 5 yr intervals, while B was presented as a new alternative with fewer thinnings at 5–15 yr intervals for increased cost efficiency. Their differences in volume production and diameter growth are negligible, and they both seem realistic under current conditions and are widely applied in Sweden (Agestam et al. 1995).

The relationship between stand age and dominant height, or site index, is a widely applied indicator of yield potential. It is generally closely correlated with volume production capacity (Sterba 1982). This relationship is often used as the basic element in growth and yield model sets that are used for yield prediction, and the evaluation of alternative treatment regimes. Timber dimensions and quality are particularly important elements in yield prediction for oak, because only high-quality timber is appreciated and priced well, and poor-quality and small-dimensioned wood has very little use.

The purpose of this study was to examine the yield potential of oak stands in Finland and its dependence on geographical location and site fertility. Because of the small number of homogeneous stands with a sufficient area and the lack of increment data, it was not possible to construct proper site index curves and growth and yield models. Consequently, the Swedish yield models and associated management programmes (Carbonnier 1975) were used as a reference, against which the existing Finnish stands were compared in terms of site index, volume growth and stand structure. External wood quality and the proportion of high-quality timber in the existing stands were also examined.

MATERIALS AND METHODS

Selection of study stands

Three data sets were combined to form the study data.

Data set 1. This included 11 stands. They were selected among 60 planted oak stands presented as candidates by the Finnish Forest and Park Service, the regional Forestry Centers, local Forest Management Associations, cities and towns, and members of the Finnish Dendrological Society, and others after targeted and public enquiries (Table 1, stands 1–11). Pure even-aged planted or direct seeded stands with at least 3 m dominant height (H_{dom}, the average height of the 100 thickest trees ha^{-1}) were accepted. The admixture percentage of other tree species could not exceed 10% of basal area, and a minimum core area of 0.1 ha with no edge effect was required. About 50% of the candidate stands were discarded on these criteria.

The 11 stands were selected among the 30 remaining candidates to ensure sufficient representation in age classes and geographical areas. The country was divided into three zones (Fig. 1). Zone I represented the natural distribution of oak, also including a great majority of the cultivated oak stands. In zone II, some cultivation in terms of forest regeneration or afforestation has been practised in the past. Zone III included the rest of the country with only experimental stand cultivation in the past. In zones II and III, all acceptable stands (7) were included in the sample. In zone I there were already plenty of stands in the two other data sets available, and only one stand in each age class (11–40, 41–80, and ≥81 yrs) was selected at random from the 10 stands with the greatest area.

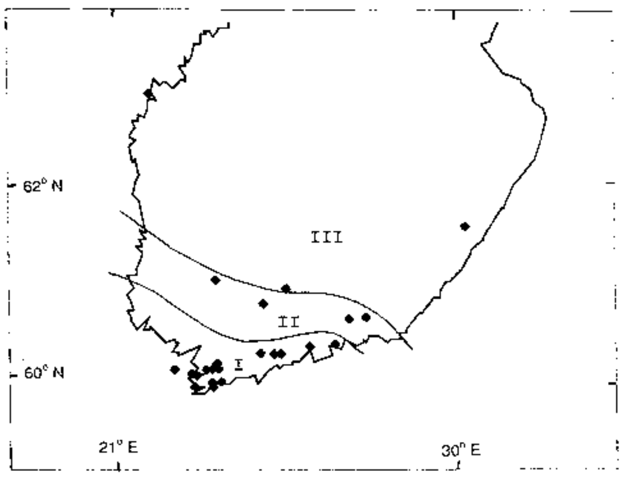

Fig. 1. Location of the study stands, and the applied geographical zoning.

Data set 2. This consisted of five stands with old permanent plots (Table 1, stands 12–16). They were homogeneous stands at least 0.15 ha in area, and they met the same structural criteria as for stands in data set 1.

Data set 3. This consisted of seven stands with permanent plots (Table 1, stands 17–23). They had been subjectively selected from known plantations on the coastal strip (zone I) constituting homogeneous stands of at least 0.15 ha in area.

The studied stands were homogeneous, pure for species and one-storey, except for stand 6 with a spruce admixture of equal height with the oak, and stands 8 and 21 with a dense broadleaved understorey. Data on establishment (e.g. provenance, stocking, planting stock, cleaning) and management (e.g. thinning, pruning) practices were incomplete or totally lacking in many stands. Most stands had not

Table 1. *Basic stand parameters*

No.	Zone	Area (ha)	Site type	Age (yrs)	H_{dom} (m)	H_{100} (m)	N (ha^{-1})	G (m^2 ha^{-1})	V (m^3 ha^{-1})
1	I	0.3	Gro	90	28.2	29.2	141	17.5	227
2	I	1.0	OMT	55	22.6	29.5	481	25.1	269
3	III	0.2	OMT	70	18.6	21.8	410	17.7	148
4	III	3.0	OMT	38	15.2	26.1	414	15.4	96
5	II	0.4	Gro	70	24.5	28.1	283	31.0	337
6	I	3.0	Agr.	28	11.4	25.6	892	11.5	63
7	II	0.3	MT	60	17.8	22.7	481	22.6	168
8	II	1.4	OMT	60	20.6	25.9	605	25.3	205
9	II	0.3	OMT	65	19.8	23.9	1160	26.9	222
10	II	0.5	OMT	95	22.7	23.1	382	26.7	275
11	I	0.2	Agr.	48	23.4	32.7	255	11.2	127
12	I	1.0	Agr.	63	20.3	24.9	430	19.0	179
13	I	0.2	Agr.	63	22.1	26.9	600	27.0	259
14	I	0.3	Agr.	63	21.8	26.6	840	25.5	251
15	III	1.5	Agr.	66	19.6	23.5	213	10.6	97
16	I	1.0	Gro	60	24.6	30.4	220	21.3	254
17	I	0.5	OMT	24	10.3	23.0	1400	11.6	56
18	I	1.0	OMT	18	5.6	27.0	1413	1.8	6
19	I	1.0	OMT	75	23.6	24.3	300	18.0	190
20	I	0.3	OMT	51	19.6	26.9	430	21.3	193
21	I	0.3	Agr.	18	7.5	23.5	1580	7.1	28
22	I	0.5	OMT	61	19.1	24.0	460	18.8	174
23	I	0.9	Agr.	71	24.6	27.1	390	20.8	257

Zones I–III: see Fig. 1.
Site type: Gro: Grove; OMT: *Oxalis–Myrtillus* type; MT: *Myrtillus* type (Cajander 1909); Agr.: afforested agricultural field. H_{dom}: dominant height (mean height of 100 thickest trees ha^{-1}; m); H_{100}: site index (H_{dom} at age 100 yrs; Carbonnier 1975, m); N: stocking (no. of oak stems ha^{-1}); G: basal area (m^2 ha^{-1}); V: stem volume (m^3 ha^{-1}).

been managed at all or had been only very lightly thinned at very irregular intervals after the establishment stage.

Sample plots and their measurements

Data set 1. One circular plot per stand with a radius of 10–15 m was placed at the midpoint of the stand in summer 1993. All trees were measured for breast height diameter (d) and stem defects were recorded with a simple qualitative scale intended to distinguish trees with substantially inferior quality than average (normal, crooked, forked, excessive branching). The five thickest and 25 other trees were systematically selected as sample trees and measured for diameter at 6 m height (d_6), height (h), height of live crown, fork height and the upper limit of the sawlog part of the stem. There is no generally applicable quality classification for oak timber in Finland, but in general, users appreciate only high-quality oak. A rather strict classification was applied in defining sawtimber, using simplified criteria applied by the Fiskars Corporation, the pioneering user and manager of oak in the country (Stig Nordman, pers. comm.). The minimum top diameter was 18 cm, and the minimum log and sawlog partition length 2 m. The maximum branch diameter was set at 2 cm, including also epicormic branches. Otherwise, no defects of any kind were allowed. The sawlog proportion was cut short below any major defect (large branch, crack, fork, distinct crook, or others). If a defective stem part could be distinguished between intact parts, its volume was subtracted from the sawlog volume.

Data set 2. The sample plots had been established several decades before, with one rectangular plot of 0.05–0.16 ha in each stand and a buffer zone at least 5 m in width. They were measured in 1993 using the same protocol as in the first data set, except that about 15 trees per stand were sampled. Stem defects and sawlog limit were not measured except for stand 15 in the remeasurement.

Data set 3. In each stand a rectangular plot with a minimum area of 0.05–0.1 ha plus a buffer zone at least 5 m in width was established in summer 1990. At that point, all trees and 20–40 sample trees were measured for the same parameters as those in data set 1, except that the stem defects and sawlog limit were not measured. The plots were remeasured in 1995, adding all the parameters that had been measured in data set 1. There were no remeasurement data available from stand 18 because it had been destroyed for construction. Slight thinnings from below and irregular removals of individual trees had occurred in the stands between the two measurements (average 10.6% of volume, range 0–19% by stands).

Treatment of data

Stand level data were calculated with the KPL program package of the Finnish Forest Research Institute (Heinonen 1994). The taper curve models of Laasasenaho (1982) were used to calculate total and partial stem volumes based on d, d_6 and h. They do not include specific functions for oaks but for pine, spruce, birch, aspen and alder only. The performance of the three basic functions was tested with the oak volume functions of Hagberg & Matérn (1975). The pine function performed best for the oak, resulting in an average 0.4% overestimation of total stem volume (Valkonen et al. 1995). Therefore, it was used here. Two alternative sawlog volumes were calculated for each tree. The potential stem volume (v_{pot}) was calculated as if there were no stem defects, and all of the stem volume below the top diameter 18 cm was assigned to sawlog. The actual sawlog volume per tree (v_{act}) was calculated using the same criteria as in the field measurements.

Stand volume increments in absolute and relative values were calculated in the permanent plot data of data sets 2 and 3 with two consecutive measurements at a 5 yr interval. Since stump diameters were not measured, the volumes of removed trees at removal were estimated from initial diameters and heights with linear regression models, the parameters of which were estimated standwise from those of the remaining trees. This was considered justifiable because the average diameter and height of the removed trees did not deviate significantly from average stand values. The midpoint of the observation period was used for growing time if the exact removal time of an individual tree was not known.

Analyses

The observed height–age relationships were placed on the site index curves of Carbonnier (1975) and their site index values (H_{100}) were calculated, grouped and compared with each other. Possible geographical gradients were explored by cross-tabulating the site index value by zones (Fig. 1) and calculating its correlation coefficient with the average annual temperature sum (sum of average daily temperatures above 5°C for the growing season, degree days) for the years 1960–1990. To compare the existing stand structures with those suggested by an established management regime, the observed number of stems (N), basal area (G) and total stem volume (V) were compared standwise with the respective values in the tables for the management regime B of Carbonnier (1975). The table with the closest site index class of $H_{100} = 24$ m or 28 m was used. The tables with the slightly higher production capacity (Tables XI.5 and XI.8), defined by the fine particle content of the soil (40% vs 50%), were chosen from the two alternatives for each site index class to avoid any potential overestimation. The values after thinning for the respective 5 yr period were used. Four stands were too young for this comparison (nos 6, 17, 18 and 21).

In addition to stands where quality parameters were not measured (nos 12–15), data from stands 6, 17, 18 and 21 were not used in the examination of tree quality and sawlog volumes because the average tree volume was still too small for the presence of major sawlog proportions. The two sawlog options, calculated at tree level (v_{pot}, v_{act}), were compared in terms of stand totals (V_{pot}, V_{act}). To establish a framework for the comparison of stands of different development stages, regression models indicating smoothed average relative values of V_{pot} and V_{act} (% of stand total volume) for a given dominant height in these data were constructed. A linearizable formulation that represented theoretically and empirically realistic curves with intercepts at 14–15 m H_{dom}, and asymptotes at 100% was chosen. The parameters were estimated with the ordinary least squares method in the stand data. Observed stand volume increments (data sets 2 and 3) were compared with the estimates given by Carbonnier's (1975) models for dominant height growth, mean height and form factor, and basal area increment.

RESULTS

The study stands scored an average value of $H_{100} =$ 25.9 m on the Swedish site index curves by Carbonnier (1975) (Fig. 2). The values ranged between 21.8 and 32.7 m. Greater site fertility on forest land

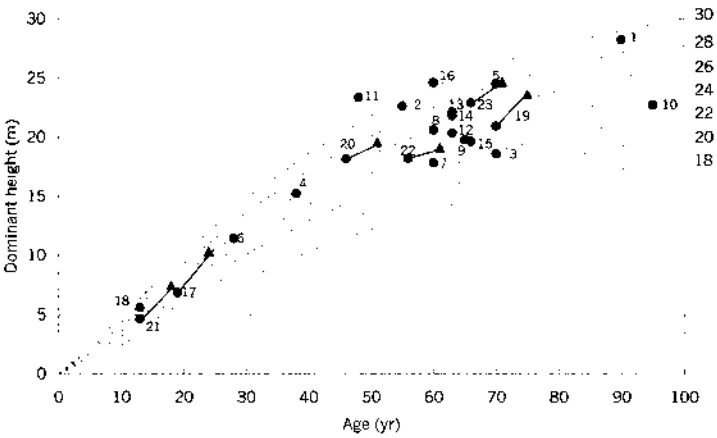

Fig. 2. Study stands on the Swedish site index curves (Carbonnier 1975). Values at the beginning (circle) and the end (triangle) of a 5 yr growing period are shown and connected with a line for the permanent plots 17 and 19–23.

Table 2. *Average value and range of the site index (H_{100}, m) by geographic zones (I–III, see Fig. 1) and site types*

Zone	Grove	OMT	MT	Agric.
I	29.8 (29.2–30.4)	25.6 (23.0–29.5)	–	26.8 (23.5–32.7)
II	28.1 (–)	25.0 (23.1–26.9)	22.7 (–)	–
III	–	24.0 (21.8–26.1)	–	23.5 (–)

Site type: OMT: *Oxalis–Myrtillus* type; MT: *Myrtillus* type (Cajander 1909); Agric.: afforested agricultural field.

(MT, OMT, grove), according to Cajander's (1909) site type system based on ground vegetation patterns, seemed to be associated with a higher site index, as expected (Table 2). Former agricultural fields showed an intermediate average value and a very large dispersion in index values. There seemed to be a slight geographical gradient in the data, with lower site index values towards the north within equal site types. The site index showed a positive correlation ($r = 0.40$) with the temperature sum, but it was not significant ($p = 0.061$). The H_{100} on the six permanent plots that were intact in the second measurement increased from 24.9 to 26.3 m (5.5%) during the 5 yr observation period.

Comparison of the stand parameters with those indicated by the respective management regimes of Carbonnier (1975) indicated that most stands were considerably overstocked (Table 3). As a consequence, the average tree stem volume was 8% lower in the studied stands than in the reference regimes.

Estimates of the increments of removed trees were included in the stand increment figures in Table 4, contributing 6.1% to them on average. Carbonnier's (1975) growth models grossly underestimated growth in the two youngest stands (average ratio observed/estimated = 206%), but the estimates were consistent with observed growths in the middle-aged stands (average ratio = 93%).

Only 35% of the sample trees were assigned to the normal quality category. The rest had at least one defect that reduced or had the potential to reduce the sawlog proportion of the tree. When only the most serious defect was taken into account, forking was the most common cause with 37% of the reduction in sawlog assigned to it, but excessive branching (29%), cracked stems (19%) and crooks (15%) were also com-

Table 3. *Average stand parameter values, and average relative values and their range in the study stands*

Value	*N*	*G*	*V*	*v*
Average absolute	457	21.1	203	0.53
Average relative	1.79	1.40	1.38	0.92
Minimum relative	0.53	0.74	0.77	0.40
Maximum relative	4.46	1.95	1.82	2.07

Relative value = parameter value divided by that in the respective Swedish management regimes in Tables XI.5 and XI.8 in Carbonnier (1975).
N: stocking (stems ha^{-1}); G: basal area (m^2 ha^{-1}); V: stem volume (m^3 ha^{-1}); v: stem volume per tree (m^3).

Table 4. *Volume increment in the stands with consecutive measurements, compared with the estimates given by Carbonnier's (1975) height and volume increment models*

Stand	Age	V	I_v	Ref. I_v	Ratio
17	19	17.0	7.9	3.8	208
19	70	154.9	7.8	10.1	77
20	46	154.1	7.9	8.3	95
21	13	6.1	4.7	2.3	204
22	56	151.1	6.7	6.7	100
23	66	213.5	9.7	9.6	101
Mean			7.4	6.8	131

Age: initial stand age (yrs); V: initial stem volume (m^3 ha^{-1}); I_v: annual volume increment for the 5 yr period (m^3 ha^{-1} yr^{-1}); Ref. I_v: I_v estimated by the models; Ratio: I_v/Ref. I_v (%).

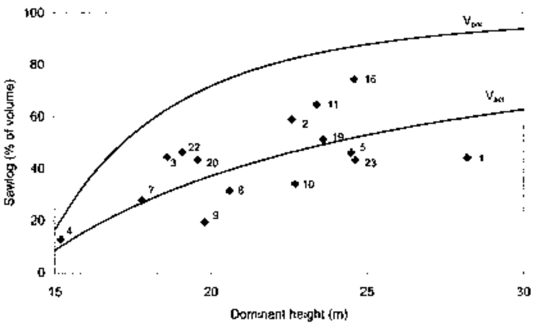

Fig. 3. Actual (V_{act}) and potential (V_{pot}) stand sawlog percentage by dominant height, calculated with models 1 and 2, and actual values (V_{act}) of the study stands.

mon. Consequently, the actual sawlog volume per tree (v_{act}) was only 58% of the potential (v_{pot}). To facilitate a comparison between stands of different development stages, models for the stand level sawlog percentages (V_{pot}, V_{act}) as a function of dominant height were constructed for both variables in the data:

$$\ln\left(1 - \frac{V_{pot}}{V}\right) = 9.987(2.537) - 3.755(0.827)\ln(H_{dom}),\quad r^2 = 0.58 \qquad (1)$$

$$\ln\left(1 - \frac{V_{act}}{V}\right) = 3.410(1.377) - 1.293(0.449)\ln(H_{dom}),\quad r^2 = 0.33 \qquad (2)$$

where V_{pot} is stand potential sawlog volume by ignoring defects, V_{act} is actual sawlog volume, V is total stem volume and H_{dom} is dominant height. The number in parentheses beside each parameter estimate is its standard deviation.

Plotting the stand V_{act} data on the curves showed that there were very large variations between stands (Fig. 3). No clear connections could be established between residuals to the V_{act} curve and geographical location, or site index. However, it seemed that the lowest relative sawlog percentages were observed in stands on low site fertility, connected to the lack of thinnings or other quality-enhancing treatments (nos 8–10). In the intensively managed stand no. 1, a high incidence of epicormic branches had set the sawlog value back substantially.

DISCUSSION

The stands in this study covered the site types and geographical area with the highest potential suitability for oak cultivation and management for wood production in the southernmost part in Finland. Most pure middle-aged planted oak stands in Finland were probably well represented in the sample. Only successful cultivations were included; total or partial failures and catastrophically damaged stands were not represented.

The study stands scored high site index values on the Swedish site index curves (Carbonnier 1975), which were based on material from locations over 600 km to the south-west on average. The highest site index value in the material of Carbonnier (1975) sustained in successive measurements was about $H_{100} = 30$ m, which was exceeded by two stands in this study. The lowest encountered value (21.8 m) was also much higher than that of 17 m in Carbonnier's (1975) material. High density could have influenced the height–age relationship in the study stands, resulting in the overestimation of the site indices that were constructed with observations from the substantially sparser Swedish stands.

A slight diminishing gradient towards the north seemed to exist in site index within the study area, but it was not significant. Site types (Cajander 1909), or rather, aggregated site type classes, based on ground vegetation, seemed to reflect productivity differences, but the dispersion within a type was very large. The most fertile type grove seem to represent an average $H_{100} = 28–30$ m in Finland, and the *Oxalis–Myrtillus* type $H_{100} = 24–26$ m, the higher value representing the southernmost zone (I) and the lower one zone III. Former agricultural fields showed a very high degree of variation, from 23.5 to 32.7 m, and an average value is not relevant here. Variation within the zones was also very pronounced, but the highest values, $H_{100} > 27$ m, seemed to be concentrated on zone I. Site variables other than site type (e.g. soil properties) were also measured, but the material turned out too small for relevant analyses.

It seems irrelevant to try to establish a close link between the site index and average volume production capacity of oak stands in Finland. Volume growth is strongly controlled by the stocking level, a crucial decision arising from the management objectives. When aiming at large-dimensioned ($d = 70-90$ cm) high-quality oak timber in long rotations, as in Sweden and Denmark (Henriksen 1988), volume growth is substantially reduced owing to the retention of a very low stem number in the stands. According to the yield table of Carbonnier (1975), the final crop should consist of only 45–118 stems ha^{-1}. The maximum mean annual volume increment (MAI) of such stands on a site with $H_{100} = 28$ m would be 6.3 m^3 ha^{-1} yr^{-1}, achievable at the age of 90 yrs, which is still rather young compared with projected optimal rotations of 120–200 yrs (Krahl-Urban 1959, Assman 1961). A planted Norway spruce [*Picea abies* (L.) Karst.] stand would yield an MAI of 11.5 m^3 ha^{-1} yr^{-1} on a similar site, $H_{100} = 33$ m, in Finland, according to the models of Vuokila & Väliaho (1980). For a planted silver birch (*Betula pendula* Roth) stand the respective MAI would be 9.9 m^3 ha^{-1} yr^{-1} (Oikarinen 1983). The volume increments were on average higher than predicted by the models of Carbonnier (1975). The models matched observations very well in the middle-aged stands, but there was a major difference in the youngest stands and also some deviation in the two oldest ones. Possible explanations include model inflexibility at the limits of its construction data or, for unknown reasons, a growth acceleration in these two stands compared with their previous performance. The role of annual growth variations also remained unknown; this may have been considerable since the observation period was only 5 yrs. Increments of the removed trees were probably slightly overestimated in the calculations, but the effect was negligible as their total contribution to the average stand volume increments was only 6.1%.

A major weakness in the wood quality study was that there is no generally accepted quality classification for oak in Finland. The applied quality classification reflected the requirements of one company only, albeit the major user and buyer of oak in Finland (Stig Nordman, pers. comm.). The classification applied in 1994 by one of the major Swedish oak users, AB Gustaf Kährs, was used as an additional reference. The quality requirements vary greatly between users and uses, and they may also change in time. In addition, internal defects could not be accounted for. Consequently, the results and the models must not be applied as a general prediction method for sawlog volumes.

The external quality of the trees was generally poor. Branching, forks, stem cracks and crooks were very common. The defects reduced the sawlog proportion by an average of 40% from that of the estimated potential, i.e. compared with trees with the same diameters (d and d_6) and height but without defects. The proportion of high-quality trees could have been substantially increased through thinnings and pruning, but most stands had been growing almost without any purposeful management. However, despite the high proportion of defective trees, the existing stands are far from being hopeless in terms of future sawlog production because there is a fairly large number of potentially high-quality trees in most stands.

The results seem to indicate a high volume growth potential of oak stands in southern Finland. The conclusion of Ollinmaa (1952), that there is no major difference between oak stands within the natural distribution area and those outside it, seems to be justified. However, there are no objective criteria for delineating geographical areas where oak management would be a profitable option. Based on a comprehensive inventory of existing stands and trees, Ollinmaa (1952) presented such lines, putting the northern limit of productive forestry with oak at about 100–200 km north of the natural distribution area. However, that limit was based on nothing but subjective judgement; neither objective decision criteria nor reliable productivity estimates were available. The survival and growth potential of oak is controlled by local, small-scale site and climatic variations to a much greater degree than by country-level climatic gradients, as proven by the solitary trees and tree groups on the northern coast of the Gulf of Bothnia (Ollinmaa 1952) and even up to the polar circle. In addition, the profitability of oak cultivation and management in Finland as a whole remains an open question. Cost and income estimates would be arbitrary, since uncertainty prevails in relation to most economic parameters. Above all, wood quality requirements and prices are determined on the market for oak, which currently is almost non-existent in Finland.

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