Modelling the Dynamics of Wood Productivity on Drained Peatland Sites in Finland

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The dynamics of wood productivity on drained peatland sites was analyzed from the covariance structure generated by stand yield data of repeatedly measured permanent sample plots in 81 Scots pine (*Pinus sylvestris* L.) or Norway spruce (*Picea abies* Karst. (L.)) stands with admixtures of birch (*Betula pubescens* Ehrh.). The site production potential, considered a latent variable, was assumed to follow an autoregressive process over time elapsed since drainage. As a measure of the latent variable, a relative growth rate (RGR) index was determined for all stands at the time of drainage and at four successive measurement time points following drainage (on average 16, 23, 30, and 41 years). The index was calculated as the site index of an upland conifer stand with the ratio of periodic volume growth and standing volume and adjusted by changes in stand stocking and thinning. The observed covariance structure was described by fitting a structural equation model to the data of RGR indices. When only the post-drainage measurement times were included, a quasi-simplex model with equal error variances and equal structural parameters at different measurement times fit the data well indicating a permanent covariance structure among the different measurements. Including the measurement at the time of drainage resulted in a non-permanent structure. The stand parameters at the time of drainage were poorly correlated with post-drainage growth.

A considerable increase in the wood productivity of the sites was observed, being greatest during twenty years after drainage and continuing up to 40 years since drainage. This was concluded to be due to changes in site properties rather than stand structure although the effects of the single factors could not be analytically separated from one another. Our modelling approach appeared to improve long-term site productivity estimates based merely on botanical site indices.

Keywords autoregressive process, forest drainage, site productivity, stand development, structural equation models
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1 Introduction

The wood production potential of forest sites can be estimated in several ways. The principal methods can be grouped into two main categories: site index methods, and botanical methods. Site index methods, based on stand characteristics such as dominant or median height versus stand age, apply best to stands with a clear dominance of one tree species and an even-aged stand structure. When applying site index methods to predict future growth one also assumes rather constant climatic and edaphic conditions over the prediction period.

Botanical methods, based on the composition of vegetation as an indicator of soil fertility and moisture, have long been used for describing site productivity. They have proved appropriate especially in semi-natural forests with varying tree species admixtures and management histories. A well-known example of predicting site productivity through botanical site type evaluation is the integration of botanical site types of mineral soil sites in southern Finland (Cajander 1909) and empirical stand-level yield data into a comprehensive system of yield tables for forest site types (Ilvessalo 1920). Subsequently, the Finnish forest site scheme was developed into a mixed system by introducing growth and yield models based on height/age index curves and an empirically indicated correspondence between the site indices and botanical site types (Gustavsen 1980, Vuokila and Väliaho 1980). Like site index methods, botanical methods also presuppose constant climatic and edaphic conditions over the prediction period. In addition, they often assume a relatively undisturbed site or stable state of the understorey vegetation.

Studies on site productivity on peatlands have been carried out mainly in the Nordic countries, especially in Finland, where more than 5 million ha of peatlands and paludified mineral soils have been drained for forestry (e.g. Paavilainen and Päivänen 1995). These studies, mostly based on botanical methods of site evaluation (e.g. Lukkala and Kotilainen 1951, Huikari 1952, Heikurainen 1973, Hånell 1984, Keltikangas et al. 1986), have provided appropriate guide-lines for selecting sites to be drained and maintained for forestry. It has also been possible to estimate the average post-drainage yield levels of different site types in various climatic conditions. However, less attention has been paid on the long-term temporal dynamics in site productivity although need for such research to establish a firm basis for sustainable forestry on drained peatland sites was identified already by Seppälä (1969) and Heikurainen and Seppälä (1973).

When considering the applicability of either traditional site index methods or botanical methods for predicting productivity of drained peatland sites, the assumptions of stand structure and site stability are unlikely to be met. Stands on forested peatlands are usually composed of trees of different ages, and there is only a poor correlation between tree age and vitality after drainage (e.g. Seppälä 1969). These two features together limit the use of stand age as an indicator of a stand's development stage. Trees within a given stand respond to drainage differently depending on, e.g., tree species, tree age and size, spatial variation in the thickness of the aerated surface peat layer, and inter-tree competition (e.g. Seppälä 1969, Hånell 1984, Miina 1994, Penner et al. 1995, Hökkä 1997, Hökkä et al. 1997). This, together with natural ingrowth, causes considerable changes in stand density and stand structure following drainage (Hökkä and Laine 1988, Hökkä et al. 1991).

As a consequence of the factors identified above, several studies have revealed significant variation in the post-drainage growth rates of stands in similar climate, within the same peatland site type, and with equal stand volumes (e.g. Seppälä 1969, Saramäki 1977, Laine and Starr 1979, Keltikangas et al. 1986). This variation may be partly explained by site-independent growth factors difficult to account for in growth analyses, such as competition, geographical variation, or previous stand treatments. However, a considerable part of the variation may be due to edaphic growth factors whose impacts may not be sufficiently accounted for by botanical site types. For instance, the removal of nutrients in timber harvesting as well as leaching of certain nutrients may deplete the mineral nutrient stores of thick-peated fen-origin drained sites, possibly impairing the development of the second-rotation stand (Starr 1982, Kaunisto and Paavilainen 1988, Kaunisto 1992, Laiho 1997). On the other hand, increased microbial activity and improved oxidation of soil organic matter (e.g. Karsisto 1979), as well as increased N and P stores in the surface peat due to compaction (Laiho and Laine 1994) following drainage, may increase tree growth in the long run.

Since considerable changes in the edaphic conditions of peatland sites may be expected following drainage, both site index and botanical methods may fail when applied to predict long-term timber productivity. In this paper, our aim is to introduce a new approach to analyzing stand yield data in order to account for the impacts of simultaneous long-term changes of site properties and stand structure on tree growth. The approach is tested with repeatedly measured data from well-managed stands, with no known interference of severe pests or abnormal development, growing on sites with fair or good potential productivity on the edaphic and climatic conditions in Finland.

2 Methods and Material

2.1 Approach

We considered the wood production potential of a given site a latent variable that cannot be assessed directly but that measurable attributes of the stand and site could be used to approximate (with error) the latent variable. We assumed that the dynamics of the latent wood production potential of drained peatland sites would follow an autoregressive model known as the Markov process. Based on a real stochastic process $X(t)$, Jöreskog (1970) has shown that the correlation structure of a stationary Markov process is consistent with the simplex structure defined by Guttman (1954). A non-stationary process with arbitrary means and variances is generated by the following model:

$$x(t_i) = \mu_i + \sigma_i X(t_i), \tag{1}$$

with $\mu_i = E[x(t_i)]$ and $\sigma_i^2 = \mathrm{var}[x(t_i)]$. $X(t_i)$ is a random variable in process $X(t)$ with the expectation value 0 and variance 1. Processes $X(t)$ and $x(t)$ have the same correlation structure. The random variables $x_i = x(t_i)$ are generated by a first-order autoregressive series:

$$x_i = \mu_i + \beta_i(x_{i-1} - \mu_{i-1}) + \zeta_i, \quad (i = 2, 3, .., \mathrm{p}) \tag{2}$$

where the residuals ζ_i are mutually uncorrelated (Jöreskog 1970).

If the observed variables are assumed to contain errors of measurement, as in our data, and the latent variables observe the Markov process, the model is considered to be a quasi-Markov simplex. Errors are assumed to be mutually uncorrelated, and uncorrelated with the true measurement, and to have the expectation value 0. The quasi-simplex model is based on confirmatory factor analysis (see Leskinen 1987, Bollen 1989) where only one variable is observed by successive measurements.

To construct a simplex model to study the dynamics of wood productivity on drained peatland sites, we considered p fallible variables y_1, y_2, ..., $y_{p,}$, where p refers to the number of successive measurements, the corresponding true variables η_i with the same unit of measurement, and the measurement errors ε_i. In the context of a more general linear structural relationship (LISREL) model, the equations defining the simplex model are, taking all variables as deviations from their means (Jöreskog and Sörbom 1989):

$$y_i = \eta_i + \varepsilon_i \qquad i = 1, 2, ..., \mathrm{p} \quad \text{and} \tag{3}$$

$$\eta_i = \beta_i \eta_{i-1} + \zeta_i \qquad i = 2, 3, ..., \mathrm{p} \tag{4}$$

where
y_i = observed variable at measurement i,
η_i = true, latent variable at measurement i,
ε_i = measurement error at measurement i,
ζ_i = residual term in the structural equation i, and
β_i = coefficient in the structural equation i.

The path diagram of the introduced basic simplex model (p = 4) is given in Fig. 1. The model implies that $\mathrm{var}(\varepsilon) = \Theta_\varepsilon = \mathrm{diag}(\theta_1, \theta_2, ..., \theta_p)$, where $\Theta = \mathrm{cov}(\varepsilon)$ = covariance matrix of the measurement errors, and that $\mathrm{var}(\zeta) = \Psi = \mathrm{diag}(\psi_1, \psi_2, ..., \psi_p)$, where $\Psi = \mathrm{cov}(\zeta)$ = covariance matrix of the residual terms.

The quasi-simplex model is statistically testable when at least four measurements are available. A simplex model is also required to be identifiable. This means that all unknown parameters of the model can be solved using the covariance matrix of the observed variables. Because only a limited number of parameters can be solved from the matrix, some parameters must be fixed to ensure the identifiability (Leskinen 1986, Jöreskog and Sörbom 1989). Also some *a priori* information on the research problem is needed to impose conditions for identification. The free parameters can be estimated using the maximum likelihood method if the observed variables are assumed to observe a multivariate normal distribution (Jöreskog and Sörbom 1989). For further properties of simplex models, see Jöreskog (1970, 1981), Jöreskog and Sörbom (1989), and Leskinen (1986).

Structural equation models can be applied to study the simplex structure (Jöreskog 1970, see also Ruha et al. 1997). The fundamental hypothesis for structural equation models is that the covariance matrix of the observed variables is a function of a set of parameters and the population covariance matrix can be produced exactly if the model is correct (Bollen 1989). A sample covariance matrix Σ generated by N observations sampled from a p-dimensional normal distribution can be shown to contain all information on the covariance matrix S of the outcome space (Leskinen 1987). The theoretical covariance matrix of the observed random variables y is:

$$\Sigma = \begin{bmatrix} \sigma_{11} & & & & \\ \sigma_{21} & \sigma_{22} & & & \\ \cdot & \cdot & \cdot & & \\ \cdot & \cdot & \cdot & \cdot & \\ \sigma_{p1} & \sigma_{p2} & \cdot & \cdot & \sigma_{pp} \end{bmatrix}$$

where σ_{ii} = var(y_i) and σ_{ij} = cov(y_i, y_j).

In the LISREL model, all elements in Σ can be expressed as functions of ψ_i, θ_i, and β_i (Jöreskog and Sörbom 1989). The residual variance can be obtained as follows: var(ζ_i) = $\psi_i = \beta^2{}_i \psi_{i-1} + \psi_i$, ($i$ = 2,3,...,p). Based on confirmatory factor analysis, the covariance matrix of the simplex model can be expressed as follows (Jöreskog 1981, Jöreskog and Sörbom 1989):

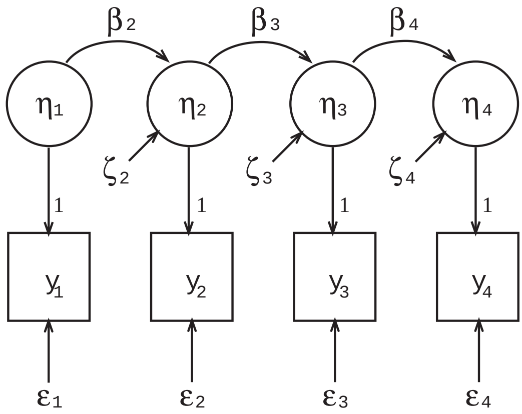

Fig. 1. Path diagram of the simplex-model with four measurements (p = 4). The parameters of the model are ω_i = var(η_i), ψ_i = var(ζ_i), θ_i = var(ε_i) and β_2, β_3, ...β_p, where
y_i = observed variable at measurement i,
η_i = true, latent variable at measurement i,
ε_i = measurement error at measurement i,
ζ_i = residual term in the structural equation i,
β_i = coefficient in the structural equation i.

The relationship between the Σ-matrices is based on the functions formulated for σ:s and the covariances of the latent variables, the covariances of the residual errors, the variances of the measurement errors, and the structural parameters. In model estimation, the difference between the sample covariances and the covariances predicted by the model is minimized (see Jöreskog 1981, Bollen 1989). The evaluation of the estimated models is based on standard errors and correlations of the estimates as well as on measures of the overall fit of the model, like the χ^2-test and the goodness-of-fit index (GFI). The residuals between the observed and the fitted covariance matrix are evaluated as well. A detailed definition of these measures and their interpretation are given by Jöreskog and Sörbom (1989 and 1993).

$$\Sigma = \begin{bmatrix} \psi_1 + \theta_1 & & & \\ \beta_2\psi_1 & \beta_2^2\psi_1 + \psi_2 + \theta_2 & & \\ \beta_2\beta_3\psi_1 & \beta_3\beta_2^2\psi_1 + \psi_2 & \beta_3^2\psi_2 + \psi_3 + \theta_3 & \\ \beta_2\beta_3\beta_4\psi_1 & \beta_3\beta_4\beta_2^2\psi_1 + \psi_2 & \beta_4\beta_3^2\psi_2 + \psi_3 & \beta_4^2\psi_3 + \psi_4 + \theta_4 \end{bmatrix}$$

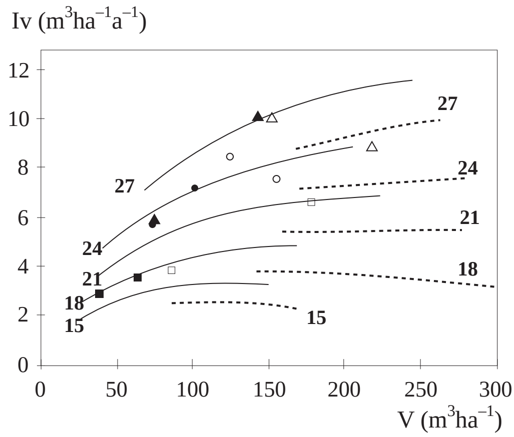

Fig. 2. Examples for defining the RGR index for three stands in the data (A = triangle, B = circle, C = square). The curves represent the relationship between the current stand volume and the past annual growth with a certain stand density prior to thinning (solid line) and after thinning (30 % removal of initial stocking, broken line) in pine plantations with different site indices (H_{100} = 15–27 m) according to Vuokila and Väliaho (1980). With the growth and volume data of a given stand, an index value can be obtained using the curves. As an example, the index values for three stands in four successive measurements were as follows. Plot A: 23.0, 27.0, 28.0, and 26.5; plot B: 22.5, 24.0, 27.0, and 26.0; plot C: 17.5, 17.5, 17.5, and 23.0. Closed symbols indicate indices defined using the pre-thinning curves, open symbols indicate indices defined using the post-thinning curves.

2.2 Relative Growth Rate Index as the Measure of Site Productivity

Considering the expected changes in site and stand properties on peatlands following drainage, the measure of the production potential should account simultaneously for the degree of site occupancy (or the proportion of the edaphic growth resources being used by the stand) and the current vitality of the stand. The measure should be simple to derive from commonly measured stand-level characteristics. We relied on the ratio of a stand's current volume increment to standing volume, earlier used to describe the development stage of drained peatland stands by e.g. Heikurainen and Seppälä (1973). We further developed this ratio into a stand-level relative growth rate (RGR) index by matching the observed stand volume, stand growth, and stand density to a reference set of growth models. The site index (H_{100} = stand dominant height at the age of 100 years) of the reference model was termed the RGR index.

The scale for the RGR indices was obtained from the growth and yield models for conifer plantations (Vuokila and Väliaho 1980) where the development of, e.g., stand volume is expressed as a function of stand age for different tree species, different thinning regimes and subsequent densities, and site index classes. We chose models where rotation periods were relatively long and removals in thinnings were 20 %, 25 %, or 30 % of the initial stand volume. Because age was not a feasible characteristic for our data, we modified the yield tables by applying the following procedure. First, we constructed nomograms where the stand-level average annual volume growth of the past 5 years was expressed as a function of current volume and stand density (number of stems per hectare), instead of stand age, for the different tree species in different site index classes (Fig. 2). Secondly, the nomogram curves corresponding to different site indices were further divided into pre-thinning and post-thinning sections. Thereafter, within the site index range of the nomograms, it was possible to determine an RGR index value, at an estimated accuracy of ca. 0.5 units, for any stand with a known treatment history, current volume, volume increment and stand density, related to a given measurement time (Fig. 2). If the stand was thinned, the index value was defined with the post-thinning sections of the nomograms derived from models where the thinning removal was close to the actual removal. We assumed that, at a given measurement time, the RGR index (y_i in equation 4 and in Fig. 1) of the stand would be the sum of the site's true timber production potential (η_i in equation 4 and in Fig. 1) and measurement error (ε_i in equation 4 and in Fig. 1). Conseptually, the RGR index is the H_{100} of a plantation with the same average volume and past growh, stratified by thinning and density class.

Table 1. Distribution of the plots into peatland site types and their estimated average relative growth rate (RGR) indices at the time of drainage in southern (S) and northern (N) Finland.

	Peatland site type[1)]	Number of plots	RGR index S	RGR index N
LhK	Eutrophic paludified hardwood-spruce forest	1	15.5	
RhK	Herb-rich hardwood-spruce swamp	6	9.0	8.0
MK	*Vaccinium myrtillus* spruce swamp	6	13.5	
KgK	Paludified *Vaccinium myrtillus* spruce forest	1	15.0	
PK	*Vaccinium vitis-idaea* spruce swamp	3		9.0
PsK	*Carex globularis* spruce swamp	3	10.0	
VSK	Tall-sedge hardwood-spruce fen	3	7.5	
VLR	Eutrophic pine fen	11		8.0
RhSR	Herb-rich sedge birch-pine fen	4	8.0	
VSR	Tall-sedge pine fen	11	7.5	
TSR	Cottongrass-sedge pine fen	8	9.5	
LkR	Low-sedge pine fen	2	7.5	
KR	Spruce-pine swamp	2	13.0	
KgR	Paludified pine forest	3	11.0	
PsR	*Carex globularis* pine swamp	2	9.0	
IR	Dwarf-shrub pine bog	9	9.5	
TR	Cottongrass pine bog	4	6.0	
VSN	Tall-sedge fen	2	0.5	
All		81		
Mean			9.3	

1) According to Laine and Vasander 1990

To enable extending the simplex model defined in equations (3) and (4) to account for the time period from drainage to the first post-drainage measurement occasion, we estimated also the RGR indices representing the time of drainage. The stand-wise pre-drainage volume growth estimates were obtained by using the data of dbh-increment cores of the sample trees recorded at the time of establishment. On 13 plots no growth data were available from the period prior to drainage. For those stands, the growth was estimated on the basis of site type and previously published information on the average growth of stands on undrained peatland site types (Heikurainen 1971, Gustavsen and Päivänen 1982, Mäkinen 1990). Because the stand volume data at the time of drainage were sometimes incomplete and both the volumes and growth rates were low, only a minor part of the pre-drainage indices were defined using the nomograms presented in the above. In most cases the RGR indices were defined using equations constructed from the 7th National Forest Inventory data for the relationship between site index (H_{100}) and stand growth (i_v) in understocked stands on mineral soils (Gustavsen, H.G., the Finnish Forest Research Institute, unpublished):

$$\text{Pine stands:} \quad i_v = -0.04 + 0.0095(H_{100})^2 \tag{5}$$

$$\text{Spruce stands:} \quad i_v = 1.03 + 0.007(H_{100})^2 \tag{6}$$

The estimated average RGR indices at the time of drainage for different peatland site types, together with the distribution of plots to site types, are shown in Table 1.

2.3 Data

To fit the model, we needed a fairly large sample of stands with a well-recorded treatment history reaching as far back as possible and with at least four successive measurements, preferably with

Table 2. Average number of years elapsed since drainage and mean standing volume and growth of the stands by measurement times (standard deviations in parenthesis) in the data.

	Measurement time 1.	2.	3.	4.
Years from	15.8	22.8	29.7	40.8
drainage	(2.68)	(2.80)	(3.50)	(5.22)
Stand volume	64.2	94.5	114.0	166.4
(m^3ha^{-1})	(42.16)	(49.71)	(54.10)	(49.71)
Past growth	3.8	5.5	5.4	6.3
($m^3ha^{-1}yr^{-1}$)	(2.2)	(2.7)	(2.9)	(2.7)

equal time steps starting from the time of drainage. Most of these requirements were met in a set of permanent sample plots located on experimental peatland drainage areas in different parts of Finland, established from the 1910's to the 1930's by the Finnish Forest Research Institute (see Gustavsen et al. 1998). The plots represent different peatland site types and stands more or less typical of the sites. Following drainage, the stands composed of Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* Karst. (L.)), and pubescent birch (*Betula pubescens* Ehrh.) with varying admixtures have been carefully managed with light thinnings, mainly from below, and ditch repairing measures when needed, to obtain the maximum stem wood yield provided by the site's potential (Paarlahti 1988). Stand development has been monitored after drainage by successive measurements on permanent sample plots.

For this study, we selected 81 permanent sample plots using the following criteria. At least four successive post-drainage measurements (not including the desired measurement at the time of drainage) at five- to fifteen-year intervals were required. The first measurement was to be from at least 10 but no more than 19 years and the last measurement from at least 33 but no more than 49 years after drainage. Plots representing the poorest site types and not matching the present drainage guidelines, as well as plots with stand growth not reaching the level corresponding even to the lowest site index class of the reference models were excluded. Coniferous stands were preferred and clearly birch dominated stands were discarded. The RGR indices for pine-birch stands and spruce-birch stands were defined by using pine stand models and spruce stand models, respectively (cf. Vuokila and Väliaho 1980). When determining the index values graphically, three plots were further discarded as outliers since their index values changed more than 15 times the average standard error between two successive measurement occasions.

The basic data set consisted of observations from 23 plots on spruce swamps or birch-spruce fens, 56 plots on pine mires, and 2 plots on tall-sedge fens (Table 1). On the average, the data covered a time period from 16 to 41 years following drainage (Table 2). The shortest and longest periods between the first and the fourth measurement were 16 and 34 years, respectively. Different methods have been used to calculate the stand-level characteristics from the basic measurement data at different times, as discussed in detail by Gustavsen et al. (1998). Although the plot-wise volume estimates may not have been fully comparable over time, they were used as such for calculating the periodic increases in stand volumes because no valid transformation procedures were available, either. Removals resulting from thinning or self-thinning during a measurement period were included in the period's end value of stand volume. The annual means of periodic volume growth were calculated by dividing the increase in stand volume by the number of growing seasons passed between the successive inventories. Detailed descriptions of the composition of ground vegetation from the time prior to drainage were available from all plots.

The simplex models assume simultaneous measurements of the observations, while the measurement interval may vary. In our data, at any given measurement time, the time elapsed since drainage varied from plot to plot. To analyze the impact of this potential source of error, we constructed a modified data set by fixing each measurement time to a certain time point in relation to drainage (15, 20, 25, 30, 35 and 40 years since drainage), instead of using the true measurement times. The RGR index for each of the fixed measurement times was linearly interpolated from the two neighbouring measurements or extrapolated from the closest measurement.

If the actual measurement time deviated from the fixed time point by no more than two years, the new indices were defined by shifting the original index values to the new fixed measurement occasions. Otherwise, the new indices were estimated by linear interpolation or extrapolation, using the trend of the most adjacent period.

3 Results

3.1 Construction of the Basic Simplex Model

The average stand volume and annual growth increased with increasing time since drainage (Table 2). The means of the RGR indices increased during the study period (Table 3). The greatest increase occurred during the first 20 years following drainage (Tables 1 and 3), and the increase continued up to 40 years after drainage. Decreasing correlations when moving away from the diagonal of the matrix (Table 3) indicated that a simplex structure existed in the data.

LISREL7 software (Jöreskog and Sörbom 1989) was used to estimate the unknown parameters in the equations (3) and (4). First, a quasi-simplex model was applied to the data. To ensure the identifiability of the model, the measurement error variances at the first and second measurements as well as at the third and fourth measurements were considered equal, i.e. $\theta_1 = \theta_2$ and $\theta_3 = \theta_4$. The χ^2-test ($\chi^2(2) = 0.00$, p = 0.982) and the goodness-of-fit index (GFI) indicated a good fit (Table 4). Because the variance estimates $\theta_1 \ldots \theta_4$ of the measurement errors were of the same magnitude they were set equal over the measurements (see Leskinen 1986). The same was done for the residual variances $\psi_2 \ldots \psi_4$ (Table 4). The new model fit the data well: $\chi^2(4) = 1.02$, p = 0.907, GFI = 0.994. Next, a perfect simplex ($\Theta = 0$) was tested. The overall fit measures decreased considerably: $\chi^2(5) = 10.05$, p = 0.074, GFI = 0.941. Also the χ^2-sequential test indicated that the perfect simplex did not fit the data ($p < 0.01$).

The quasi-simplex model was further generalized by setting all the structural parameters β_i equal. According to the measures, the model was still adequate: $\chi^2(6) = 3.01$, p = 0.807, GFI = 0.983. All parameters deviated from zero and all standardized residuals were acceptable (Table 5). The reliability of the measure was relatively high and of almost equal magnitude at all measurements (Ry_i^2 = 0.913 – 0.917). The simplex structure of the latent timber production potential could be considered permanent during the study period ($\beta_2 = \beta_3 = \beta_4 = 0.929$). Calculation of the squares of the correlation coefficients of the latent variables (Leskinen 1986) showed that the RGR index in the first measurement explained 72 % and 62 % of the variances of the RGR indices in the third and fourth measurements,

Table 3. The correlations of the current relative growth rate indices (RGR), and their means (μ) and standard deviations (s.d.) by measurements (n = 81).

	Measurement 1.	2.	3.	4.	RGR μ	s.d.
1.	1.000				18.395	4.7022
2.	0.848	1.000			20.722	4.8932
3.	0.781	0.841	1.000		20.642	5.1236
4.	0.724	0.780	0.858	1.000	22.130	4.7248

Table 4. Parameter estimates and their standard errors (s.e., in parentheses), and the reliabilities of the measures (R_{yi}^2) and the coefficients of determination ($R_{\eta i}^2$) of the initial quasi-simplex model with four measurements (N = 81). The model has the constraint $\theta_1 = \theta_2$ and $\theta_3 = \theta_4$.

	Measurement 1.	2.	3.	4.
β_i		0.974	0.964	0.856
(s.e.)		(0.079)	(0.075)	(0.063)
θ_i	2.090	2.090	1.988	1.988
(s.e.)	(0.921)	(0.921)	(0.973)	(0.973)
ψ_i	20.021	2.852	3.941	2.569
(s.e.)	(3.615)	(1.718)	(1.319)	(1.646)
R_{yi}^{2*}	0.905	0.913	0.924	0.911
$R_{\eta i}^{2**}$		0.869	0.838	0,874

* R_{yi}^2 = squared multiple correlations for y-variables = var(η_i) / var(y_i) (i = 1,2,..., p)

** $R_{\eta i}^2$ = total coefficient of determination for structural equations = 1 – var(ζ_i) / var(η_i) (i = 2,3, .., p)

Table 5. Parameter estimates (and their standard errors in parentheses) and the reliabilities of the measures (R_{yi}^2) and the coefficients of determination ($R_{\eta i}^2$) of the final quasi-simplex model with four measurements. The model constraints are $\beta_2 = \beta_3 = \beta_4$; and $\theta_1 = \theta_2 = \theta_3 = \theta_4$.

	Measurement 1.	2.	3.	4.
β_i		0.929	0.929	0.929
(s.e.)		(0.037)	(0.037)	(0.037)
θ_i	1.974	1.974	1.974	1.974
(s.e.)	(0.625)	(0.625)	(0.625)	(0.625)
ψ_i	20.636	3.250	3.250	3.250
(s.e.)	(3.576)	(0.983)	(0.983)	(0.983)
R_{yi}^2	0.913	0.914	0.916	0.917
$R_{\eta i}^2$		0.846	0.848	0.851

Table 6. Parameter estimates and their standard errors (in parentheses) and the reliabilities of the measures (R_{yi}^2) and the coefficients of determination ($R_{\eta i}^2$) of the quasi-simplex model for five measurements.

	Measurement[1)] 0.	1.	2.	3.	4.
β_i		0.560	0.939	0.939	0.939
(s.e.)		(0.193)	(0.035)	(0.035)	(0.035)
θ_i	2.236	2.236	2.236	2.236	2.236
(s.e.)	(0.613)	(0.613)	(0.613)	(0.613)	(0.613)
ψ_i	8.779	17.682	2.841	2.841	2,841
(s.e.)	(1.846)	(3.269)	(0.921)	(0.921)	(0.921)
R_{yi}^2	0.797	0.901	0.903	0.905	0.906
$R_{\eta i}^2$		0.135	0.864	0.866	0.868

[1)] Average time (years) since drainage: 0. = 1.0, 1. = 15.8, 2. = 22.8, 3. = 29.7, 4. = 40.8

respectively. The model (Table 5) was accepted as the final model describing the dynamics of timber production potential of the sites during an average period of 16 to 41 years since drainage.

3.2 Extensions of the Model

A model similar to that for four measurements (Table 5) was applied to the extended data set including the estimated pre-drainage RGR indices. All θ_i were fixed equal. The residual variances of the structural equations for the last three measurements were set equal, as well as the structural parameters $\beta_2...\beta_4$ (Table 6). Compared to the final model with four measurements, the fit measures decreased considerably but the model was still acceptable: $\chi^2(9) = 15.81$, p = 0.071, GFI = 0.925. The reliability of the measure was low at the first measurement but increased considerably in the subsequent measurements (Ry_i^2 > 0.901). The simplex structure was not permanent during the study period. The pre-drainage RGR indices predicted poorly the production potential measured at the first post-drainage occasion ($R\eta_i^2 = 0.135$). Among the later measurements, the coefficient of determination was still much higher (0.864–0.868).

When trying to apply quasi-simplex and perfect simplex models to the modified data set with four fixed measurements times (15, 25, 30, and 40 years from drainage), none of the models fit the data with all measurements included. When substituting the second fixed measurement time (corresponding to 25 years since drainage) by another measurement time (20 years from drainage), a perfect simplex fit the data but the structural parameters were not equal. After equalizing the structural parameters and the residual parameters at the two last fixed measurements, and still excluding the 25-year-measurement, a perfect simplex resulted in a good fit: $\chi^2(7)$ = 7.55, p = 0.374, GFI = 0.962.

4 Discussion

4.1 Factors Affecting the Estimation of RGR Indices and Site Productivity

Our results showed that it is possible to model the dynamics of wood productivity on drained peatlands in terms of a covariance structure generated by stand-level growth and yield data from repeatedly measured permanent sample plots. The temporal structure of the latent production potentials of the sites and the RGR indices used as a measure of the latent variable, could be expressed by a simple autoregressive quasi-simplex model where the structural parameter β had a constant value throughout the measurements. This means that the plots having, e.g., low index values at the beginning tended to obtain low values throughout the study period. Although the structural parameters had a constant value, the process was non-stationary since the RGR index means increased over time. This result must be interpreted as an interactive effect of a true increase in the wood production potential of the sites and a possible artificial effect related to determining the RGR index values with the help of reference models. In the following, the significance of these effects, as well as the reasons for the increasing productivity are discussed based on our modelling approach as well as on results from other studies.

According to our approach, the true site production potential was considered a latent variable and the other factors affecting growth, and not being accounted for by the RGR index, were considered as parts of the measurement error. Assuming that the dynamics of the latent production potential were correctly accounted for by the final quasi-simplex model (Table 5), there remain two potential main sources of error related to the measured variable RGR: (i) the volume and growth determinations at the different measurements which can't be further examined from the data available, and (ii) the use of the reference models to guide the determinations of the RGR index values, on which the model extensions may shed some more light.

Extending the model to fit the modified data set with four fixed measurement times resulted in a perfect simplex structure, i.e., by fixing the measurement time points and estimating the corresponding RGR index values by linear interpolation, measurement error became insignificant. This implies that a significant part of the measurement error in the basic quasi-simplex model was due to the variation in the measurement time points relative to time elapsed since drainage. The reduced fit resulting from extending the model to include the pre-drainage RGR indices was more or less expected because, e.g., volume growth of stands growing on undrained peatlands is mainly influenced by the water regime and less by site fertility (Heikurainen 1971, Mäkitalo 1985, Gustavsen and Päivänen 1986). Consequently, stand characteristics at the time of drainage predict post-drainage timber production poorly, which was specifically indicated by the non-permanent structure of the quasi-simplex model. To some degree, the problems with the reliability of the model at the pre-drainage measurement may have been due to the different method in estimating the RGR index values. Unfortunately, no information of this potential impact could be gained from the analyses.

The RGR index means continued to increase up to the end of the study period, even after the expected 15 to 20-year growth response to water level draw-down. If not due to a true increase in the sites' production potential, the observed trend could be born out of potential bias in the determination of the RGR indices, the possible sources of which are discussed in the following. First, the RGR index values could have been affected by ingrowth to which the initially sparse and uneven-sized peatland stands are usually subjected during several decades following drainage (Hånell 1984, Hökkä and Laine 1988). In our data, however, the impacts of ingrowth were probably rather small due to the intensive management of the stands with light thinnings mainly from below and the subsequent decrease in the average stem number per hectare since the second measurement (data not shown; see also Gustavsen et al. 1998). However, as far as any ingrowth exists and as the stand structure simultaneously changes from an uneven structure towards a more even structure, increasing stand yields are to be expected (Sterba and Monserud 1993). Secondly, the potential impacts of varying stand densities on the measured RGR indices were probably fairly well accounted for by using an appropriate set of growth and yield models, with numerous options of thinning schemes, as the reference models. As far as thinning responses are concerned, there is reason to believe that the responses of peatland stands are weaker and slower than those of upland stands (Hökkä et al. 1997). Consequently, when applying the upland reference models to the newly thinned stands in our data, one would have expected obtaining lower RGR index values than appropriate. Altogether, the impacts related to ingrowth and stand treatments do not seem to provide relevant explanations for the observed increases in the RGR indices. Most of the interest in this discussion is thus to be focused on the impacts of changing site properties, leaving the possible impact of changing stand structure somewhat open.

An instant tree-level growth response is known from earlier studies to be attributable to the improved conditions for tree growth during the first 15-year period following drainage (e.g. Lukkala 1937, Seppälä 1969, Hånell 1984, Miina 1994). This time period corresponded for the greatest change in site productivity also in our results. In some studies the growth rate of stands has been found to level out or even reverse some twenty years elapsed since drainage (Heikurainen 1980, Hånell 1984, Hökkä et al. 1997). Our results showed that, after a peak and consequent levelling out around 15 to 25 years since drainage, a slight increase in stand-level productivity is still to be expected at least up to 40 years since drainage which in many cases brings the stand to the end of the first post-drainage rotation. The reason for our results differing from those of the earlier studies may be a result of site selection. Our data come from research sites with intensively managed drainage systems. The data of Heikurainen (1980), Hånell (1984), and Hökkä et al. (1997) are from drainage areas managed for production forestry which means that the drainage systems likely had little or no maintenance during the first 20 years following the initial drainage.

Our results showing increasing productivity with increasing time since drainage are in accordance with those of Bush (1964) concerning long term individual-tree growth and especially with Seppälä's (1969) comparisons of tree growth on drained peatlands to trees of similar size growing on mineral soil sites. On the other hand, Heikurainen and Seppälä (1973) and Keltikangas et al. (1986) reported lower stand-level relative growth rates in old drainage areas than expected on the basis of site quality indices (Heikurainen 1973) and some earlier results (Heikurainen 1959). Partly these unexpectedly low growth rates may have been due to not fully accounted impacts of the relatively high proportions of thinned stands in the inventory data sets. Both Heikurainen and Seppälä (1973) and Keltikangas et al. (1986) used merely the ratio of volume growth to current stand volume as an indicator of site productivity which may have led to underestimate the sites' production potentials. In old managed stands the standing volume and growth are affected by previous commercial thinnings and, moreover, the ratio of current growth to standing volume becomes quite different from what it is in younger stands with high densities and still increasing relative growth rates.

4.2 RGR Indices versus Botanical Site Evaluation

We calculated the correlation between the RGR indices defined for the last measurement time and the botanically based site quality indices defined by Heikurainen (1973) using the vegetation composition data of the plots from the time prior to drainage. The RGR indices at the last measurement correlated positively with the site quality indices ($r = 0.465$, $p = 0.001$). Because Heikurainen's site index is a function of tree species, the correlation was also calculated for pine stands, only ($n = 66$). The correlation was weaker but still significant ($r = 0.262$, $p = 0.034$). In the north the range of the site quality indices was limited (Fig. 3) which may have weakened the correlation with the RGR indices in these data. The RGR indices, i.e., the measured wood

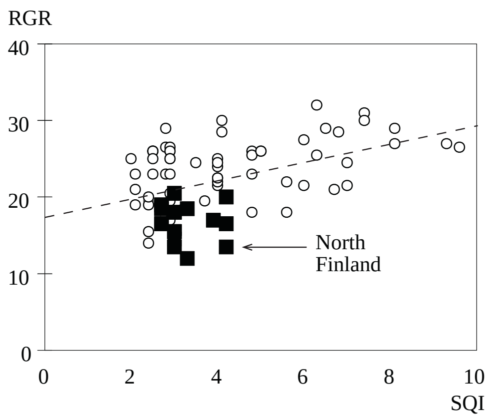

Fig. 3. Correlation of the site quality index (SQI) and the RGR index at the last measurement. Plots located in northern Finland are indicated by squares.

productivity, of sites with low site quality indices varied considerably, especially in southern Finland. Furthermore, a site of a given quality index seemed to obtain higher RGR indices in the south than in the north (Fig. 3).

The average RGR index values at the last measurement were calculated for the site types with at least three plots included in the data set. On the average, the RGR indices increased with increasing fertility of the sites (Table 7). However, e.g. cottongrass-sedge pine fens (TSR) obtained even higher indices than herb-rich sedge birch-pine fens (RhSR). Some unexpectedly high average values, as well as the rather great variation in the RGR index values related to site types of low botanical site quality indices, implied that the RGR indices were able to account for some source of variation in productivity within a given botanical site index class. This may be a result of the implicit inclusion of density, dominant species and thinning treatment in the computation of RGR index. It could also be associated with changes in site properties since drainage. Some authors have suggested that in specific circumstances, nitrogen nutrition in older drainage areas may change to more favourable for tree growth than what would be expected based on the botanical site type (e.g. Hotanen and Tonteri 1991). Also, the compaction of the surface peat layer due to water level draw-down may bring more nutrient rich peat within the reach of tree roots. It is also possible that atmospheric nitrogen deposition contributes significantly to the nutrient status of sites in southern Finland.

Table 7. Average RGR indices by site types ($n \geq 3$) at the fourth measurement time (ca. 40 years after drainage) in southern (S) and northern (N) parts of Finland.

Site type 1)	RGR index South	RGR index North	n
RhK	27.7	17.8	6
MK	26.0		6
PK		18.2	3
PsK	27.5		3
VSK	26.8		3
VLR		15.8	11
RhSR	23.0		4
VSR	26.9		11
TSR	23.7		8
KgR	16.3		3
IR	20.3		9
TR	19.4		4

1) For the abbreviations, see Table 1.

4.3 Conclusions

Our approach on modelling the dynamics of site productivity with repeatedly measured stand-level yield data from permanent sample plots appeared to contribute significantly to the site productivity predictions based merely on botanical site evaluation. It seemed evident that the wood productivity of the examined drained peatland sites increased continuously over time elapsed since drainage, partly due to changes in stand structure and stocking but probably mostly due to changes in site properties. The rate of change in the edaphic variables is most rapid immediately following drainage although some effects may only become evident as the stand growth (and nutrient demand) increases. As well, the edaphic conditions may be affected by any interventions including remedial ditching and thinnings. A drawback of the applied method was that it was not possible to distinguish the effect of single factors (i.e., initial growth response to drainage, increase in yield due to change in stand structure, and long term changes in site properties) on the RGR index means from one another. This would probably require more detailed tree-level analysis with explicit inclusion of the different effects in the model. Thus the RGR index method as such cannot be considered a general solution to measure site productivity of drained peatlands but there remains a need to develop a direct measure (site index) that would more explicitly indicate site quality in terms of wood productivity.

As to practical forestry, our results of the continuously increasing RGR indices suggest that improving productivity of drained peatland sites may be expected for several decades after drainage, provided that the drainage is properly maintained. The results on the productivity level obtained in the experimental stands are not expected to apply directly to all drained peatland sites in Finland but are more likely to represent the highest production potentials that can be achieved by best management practices on sites with fairly balanced nutrition.

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