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Site index changes of Scots pine, Norway spruce and larch stands in southern and central Finland

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ABSTRACT

The annual growth of the Finnish forests has doubled in less than a century but the reasons for the increase have been a subject of much debate. Site index aggregates the mid- to long-term impacts of variable edaphic and climatic factors on site productivity and is an important characteristic with regard to the ongoing environmental changes. We quantified changes of site index in Finland over time by applying a new approach developed in our previous study in Germany. A large data base for Norway spruce (*Picea abies* (L.) Karst.), Scots pine (*Pinus sylvestris* L.) and larch (*Larix* spp.) was available from the network of long-term growth and yield experiments in southern and central Finland. For all tree species, site indices fluctuated over time, i.e. they slightly decreased in the 1970s, followed by an increasing trend in the 1980s and a decline again in the 1990s. Apparently, the only significant change was a change point indicated for Scots pine around the year 1944; however, indication was weak due to notable limitations of the database during the respective period. Interestingly, the result of this study in Finland differs from central Europe, where Norway spruce site productivity has displayed a considerable increase since the 1950s. Potentially, the low nitrogen deposition in Finland may be of major importance accounting for the divergent changes in site productivity between Finland and central Europe. Thus, the results indicate that a large share of the growth increase in the Finnish forests might actually be due to altered management.

1. Introduction

The annual growth of the Finnish forests has doubled in less than a century (49.8 mill.m^3 a^{-1} in 1930s to 99.5 mill.m^3 a^{-1} in 2000s) (Korhonen et al., 2013). A fast increase began during the 1970s, and the rate of change has remained stable. Before the growth increase, adequacy of forest resources was regarded in Finland as an important factor limiting the national economic development. Therefore, over the past century the Finnish government has launched actions aiming to increase forest production, such as banning selective (highgrading) logging and subsidising silvicultural investments, such as drainage of peatlands, use of genetically improved seed material and advanced regeneration methods (Siiskonen, 2007; Kuuluvainen et al., 2012). Most probably, changes in silvicultural methods have contributed to increasing growth. However, the effects of the various measures have not been quantified at the level of national forest resources.

The effects of changing environmental factors on forest production have been a subject of much debate. In the boreal zone, climate change is expected to increase forest production via increased growing-season temperature, although several uncertainties remain (Kellomäki et al., 2008), especially the ones related to extreme climate events potentially causing large-scale forest damage (Seppälä et al., 2009). CO_2 enrichment and nitrogen deposition may also enhance forest growth, but attempts to quantify the effects of each factor have produced contradictory results. In some reports, a large share of the growth increase in the Finnish forests has been attributed to environmental changes, particularly rising temperatures (e.g. Hari and Arovaara, 1988; Kauppi et al., 2014). Others have discovered only minor indications of growth increases not explainable by changing silviculture or increasing growing stock (Mielikäinen and Timonen, 1996; Henttonen, 2000).

In several other European countries, forest growth has displayed a considerable increase during the latter part of the 20th century, and a number of studies suggest that part of the increase is due to environmental changes (Spiecker et al., 1996; Kahle et al., 2008; Pretzsch et al., 2014b). However, these studies have usually been based on straightforward approaches, such as comparison of consecutive tree generations at the same location or nearby stands with

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different establishment dates. Therefore, a multitude of potential influencing factors related to management history, disturbances and tree genetics need to be effectively controlled for (Pretzsch et al., 2014a).

Supporting the conclusions of an IPCC report (IPCC, 2013), modelling experiments project that temperature increase will increase forest production in Europe (Kirilenko and Sedjo, 2007), and that the increase is expected to be especially accelerated in the northern regions including Finland (Kellomäki et al., 2008). However, it is not clear if these models actually simulate forest responses realistically. The effects of elevated temperature and CO_2 measured in experimental settings and implemented in models may overestimate actual responses, because many growth limiting factors are neither well understood, nor well implemented in the models. Interactions between the causal factors further complicate the issue.

Wood production potential of a stand varies according to tree species, geographical location and site properties (e.g. Assmann, 1961). In forestry, site productivity is defined as the potential for stem volume growth under standardized stand conditions usually covering the whole production period (stand rotation). Site productivity is conventionally described by a site index, expressed as the expected height of dominant trees at a specific reference age (Assmann, 1961; Skovsgaard and Vanclay, 2008). Site index is assumed to aggregate the impacts of variable edaphic and climatic factors on site productivity.

In a previous study, we developed a new approach to detect and quantify changes of site index over time based on long-term plots of Norway spruce (*Picea abies* (L.) Karst.; "spruce") in southwest Germany (Yue et al., 2014). By using the repeatedly measured plots, we avoided the problems in cross-sectional age-height series measured from temporary sample plots and the problems of stem analysis data, i.e., over-representation of old stands on infertile sites and missing information on past stand dynamics. The results showed that in southwest Germany height growth of spruce has increased after the mid-1950s into 1990s, followed by a slight declining trend after the turn of the century. Furthermore, the approach has proved adequate to render site index series for southwestern Germany as a basis for building environmentally sensitive site index models from longitudinal data (Yue et al., 2016).

Due to different climatic and environmental conditions compared to central Europe, it is not implausible to expect a divergent trend in site index when moving northwards. As a large data base for spruce, Scots pine (*Pinus sylvestris* L.; "pine") and larch (*Larix* spp.) was available from the network of long-term growth and yield experiments in southern and central Finland, we aimed in this study to evaluate long-term changes in site index in Finland by applying the approach developed in our previous study.

2. Material and methods

2.1. Study material

The data set for this study was compiled from 145 thinning experiments with pine (107), spruce (27), and larch (11), respectively. The experiments were located in southern and central Finland and comprised in total 840 treatment plots (Table 1). The stands were even-aged, pure or almost pure stands growing on mineral soil. Most of the experiments were established at the first thinning stage in young stands with dominant height (based on the 100 largest trees ha^{-1}) ranging around 12–15 m, but some plots were also established in older stands (Fig. 1).

The aim of the experiments was to investigate the effects of thinning intensity on growth and yield of the stands. Treatments covered unthinned control plots and thinnings from below with intensities ranging from low intensity thinnings to 40% removal of stand basal area. Most of the pine and spruce experiments were used in previous studies showing that dominant height was practically unaffected by stand density and thinning practices and therefore a versatile indicator for site productivity (Mäkinen and Isomäki, 2004a,b). Thinning treatments, which might impact dominant height (i.e., thinning from above), as well as fertilised plots, were excluded from the data set.

Table 1
Characteristics of the plots.

Parameter	Unit	Mean	Std.	Min.	Max.
Scots pine					
No of plots		675			
Plot size	ha	0.12	0.04	0.01	0.25
No of measurements	N/plot	3.9	1.6	2	10
Period length	years	8.9	3.3	2	26
Elevation	m, asl	144	56	25	280
Norway spruce					
No of plots		142			
Plot size	ha	0.11	0.02	0.10	0.25
No of measurements	N/plot	6.0	2.0	2	10
Period length	years	6.1	2.2	2	14
Elevation	m, asl	123	29	80	200
larch					
No of plots	N	21			
Plot size	ha	0.20	0.12	0.10	0.5
No of measurements	N/plot	4.0	0.97	2	5
Period length	years	7.3	3.7	3	16
Elevation	m, asl	105	17	85	130

Although the oldest measurements from the pine experiments dated from the 1930s, most experiments were established in the latter part of the 1960s and early 1970s (Fig. 1). The sites were classified as the *Myrtillys*, *Vaccinium,* or *Calluna* forest site type, respectively (Cajander, 1949), which correspond to relatively fertile, relatively infertile, or infertile sites, respectively typical for pine in Finland. The stands had mainly been established by natural regeneration or sowing with seed of local origin.

The first measurements in the spruce and larch experiments originated from the 1960s (Fig. 1). The sites were classified as *Oxalis-Myrtillus* or *Myrtillus* forest site type (Cajander, 1949), which correspond to highly fertile or fertile sites typical for spruce and larch. The spruce stands were established by planting with seed of local origin. In Finland, larch is a non-native species and the experiments were established by planting for testing its suitability to local conditions. Nine of the larch experiments were Siberian larch (*Larix sibirica* Ledeb.) and two European larch (*Larix decidua* Mill.).

Following establishment, the experiments were measured one to ten times (Table 1). On each plot, stem diameter of all the trees at breast height (1.30 m) and height of randomly selected sample trees were measured. In the selection of sample trees, the probability for a tree to be selected was proportional to its diameter and the number of sample trees was ~30 per plot. The heights of the other trees were predicted using Näslund's height curve (Näslund, 1937) that was fitted for each plot with the help of the tree heights measured on the sample trees. Based on the sample tree measurements and predicted heights, dominant height was calculated for each plot and measurement (Fig. 1).

2.2. The site index model

In this study we applied the methods developed in our previous study (Yue et al., 2014) to develop the site index models, detect, and quantify changes of site index in the Finnish dataset. Therefore, the following remarks on methodology are from this previous study but have been shortened in the interest of brevity. The study of Yue