

Forest site productivity: a review of spatial and temporal variability in natural site conditions

Jens Peter Skovsgaard^{1*} and Jerome K. Vanclay²

¹Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, S-230 53 Alnarp, Sweden

²School of Environment, Science and Engineering, Southern Cross University, Lismore, NSW 2480, Australia

*Corresponding author. Tel: +46 40 41 51 28; Email: jps@slu.se

Received 25 June 2012

Indicators of forest site productivity may exhibit considerable spatial and temporal variability that should be considered in sustainable forest management. It is generally assumed that natural site conditions and, in turn, site productivity changes gradually and predictably. Our review illustrates many exceptions to this paradigm. Consequently, uni-dimensional productivity indicators such as the commonly used site index (estimated based on stand height) is not always sufficient to characterize site productivity for apparently homogeneous forest stands. To alleviate this problem, we suggest a hierarchical procedure for the estimation of forest site productivity including site mapping, unthinned reference stands (against which to measure growth performance) and adaptive modelling. The level and detail at which site mapping should be conducted (region, forest, management unit or subunit), depends on the objective (research vs. operational forestry), forest type and expected deviations in site productivity estimates compared with the cost of site mapping. Unthinned reference plots should preferably be maintained in the long term and the number of plots should increase with increasing site or stand heterogeneity (for homogeneous land we recommend one plot in 10 ha, two in 100 ha, etc.). With adaptive modelling site specific parameters can be updated at any time when new information has become available. Finally, the review indicates a need to re-define traditional measurement procedures to achieve a contemporary and rational statistical basis for the estimation of site productivity.

Introduction

Reliable estimates of site productivity are crucial for the sustainable management of forest resources. In this paper, we present and review a series of published and unpublished examples that illustrate the suitability of some fundamental principles of the concept of forest site productivity. The question we address is: 'Do concepts agree with facts?' Throughout, we refer to site productivity as the production that can be realized at a certain site with a given genotype and a specified management regime (cf. Skovsgaard and Vanclay, 2008). Site productivity depends both on natural factors inherent to the site and on management related factors.

During the twentieth century, the major principle for site assessment in even-aged forest has been the use of stand height as an indicator of productivity, with or without concern for the possible effects of management on stand growth. This practice is closely linked to three fundamental concepts of forest site productivity that emerged since the late 1800s:

- (1) site classification by stand height (the site index hypothesis),
- (2) Eichhorn's rule (on the relationship between stand height and volume growth) and
- (3) the thinning response hypothesis (on the effect of thinning on stand volume growth).

The use of stand height as an indicator of site productivity relies on the hypothesis that height growth correlates well with stand volume growth (Heyer, 1841; Baur, 1877). Eichhorn's rule claims that the total volume production of a given tree species at a given stand height should be identical for all site classes (Eichhorn, 1902, 1904; Gehrhardt, 1909, 1921). The thinning response hypothesis is often interpreted as an assertion that stand volume growth is independent of thinning practice for thinning severities ranging from the unthinned stand to the removal of approximately 50% of the maximum crop volume or basal area (Wiedemann, 1932, 1937; Langsæter, 1941; Møller, 1944, 1951, 1954).

With the maturation of field experiments and forest science, these hypotheses were revised. It turned out that, for several species and site types, the correlation between site index and volume growth may be poor, and considerable site-dependent variation may occur in total volume production at a given height (Assmann, 1955, 1959; see also Weise, 1880). This may hold even within a specified growth region and for a given, well-defined silviculture (spacing, thinning regime etc.). Additionally, the specific thinning response (both nature and relative amount) may depend on tree species, age and site (Assmann, 1950, 1954, 1956, 1961, 1970).

Total volume growth at a given stand height has been identified as the yield level, production class or increment level. The yield

level is thus another measure of site productivity in terms of volume production per unit of height growth. Maximum basal area, the basal area at which volume growth peaks and the basal area at which volume growth is reduced by 5% compared with its peak value have been identified as the natural, optimal and critical basal area, respectively. In line with this terminology, the revised hypotheses are commonly known as Assmann's yield level theory and Assmann's theory of natural, optimal and critical basal area.

The application of the yield level theory for the estimation of site productivity has been hampered by the apparent lack of simple indicators, which are not overly complicated to use in forestry practice. Recently, this was overcome through a three-dimensional model of the relationship between stem number, quadratic mean diameter and stand basal area (Sterba, 1975, 1981, 1985, 1987). The model relies on site-specific levels of maximum basal area at any stage of stand development. Given this, a stand density index based on the combination of stem number and quadratic mean diameter provides an indication of the yield level, which may be used to adjust height-age-based estimates of site productivity.

The development of these site productivity concepts has been led by foresters and scientists in Central and Northern Europe and is closely linked to improved design and maturation of forest field experiments, international cooperation in forest science and developments in forestry practice. The general awareness of these concepts varies from country to country, but they appear to be deeply rooted fundamentals of the dominant paradigm in forestry and in forest science (Skovsgaard and Vanclay, 2008).

Another important component of the paradigm is that forest growth can be modelled in a smooth and continuous manner, and that spatial changes can be handled as gradual changes along one or more gradients (with the exception of thinning). It is also still widely held that site productivity should be constant and invariant within site types that are uniform with respect to climate, topography and soils.

Many studies substantiate the prevailing paradigm of smooth development, gradual changes and non-chaotic behaviour of forest growth (see, for example, forest mensuration texts such as Philip, 1994; Avery and Burkhart, 2002; Husch *et al.*, 2003; West, 2004; and forest modelling texts such as Vanclay, 1994; Pretzsch, 2009; Weiskittel *et al.*, 2011; Burkhart and Tomé, 2012), but exceptions frequently occur. In this paper, we present examples in the following sections that either contradict this hypothesis or highlight other problems relating to the three fundamental principles of forest site productivity. We focus on spatial variability in site conditions and temporal variability in productivity.

Spatial variability in site conditions

Spatial variability in site conditions, involving topography and soil, contribute to spatial variability in stand conditions and may dampen or reinforce the natural variability in the size of trees due to genetic variation and silvicultural treatment. This may in turn, influence estimates underpinning site productivity indicators. Often, stand boundaries coincide with changes in site conditions, reflecting either a natural change in vegetation type or a planned, site-specific management approach.

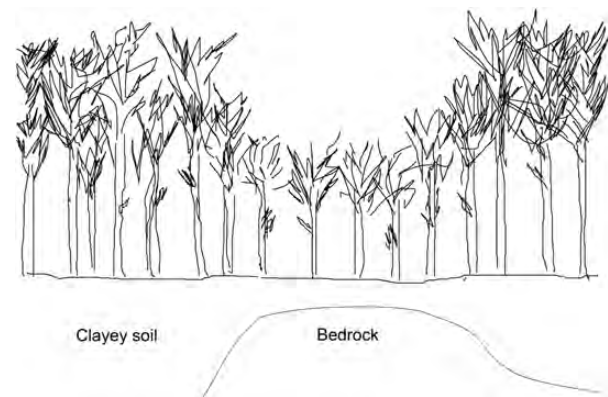


Figure 1 Red oak on alluvial deposits in France (based on Meredieu *et al.*, 1996). An outcrop of bedrock at a depth of 2 m significantly increased mortality and reduced height growth, indicating a considerable short-range reduction in site productivity. Note that the horizontal and vertical scales are not identical.

When assessing site productivity for a specific forest stand, the assumption usually is that site conditions are homogeneous and that stand conditions are uniform. Here, we present five examples to demonstrate that this may not always be true.

Red oak on alluvial deposits in France

The first example deals with a plantation of even-aged red oak (*Quercus rubra* L.) growing in the Dordogne valley in the southwest of France (Meredieu *et al.*, 1996). The area was previously farmed, relatively flat, and situated on a terrace of alluvial deposits.

Figure 1 shows a schematic profile of a 15-year-old oak stand that was studied intensively for the relation between short-range soil variability and individual tree height growth. In this example, an outcrop of bedrock at a depth of 2 m significantly increased mortality and reduced height growth, indicating a considerable reduction in site productivity compared with adjacent parts of the stand. Because of the relatively shallow soil in the affected area, this reduction in productivity is likely to be permanent.

The detection of differences in site conditions and delineation of site types on un-afforested, former farmland can be challenging, and may require detailed site mapping with frequent records of soil conditions to below rooting depth. Once afforested, variability in site conditions may be reflected in tree growth, but these differences in vigour may be inexplicable unless site conditions are thoroughly mapped. More importantly, site mapping should provide for site-specific species selection as well as land use and management practices.

Mountain ash on volcanic soils in New Zealand

The second example deals with plantations of even-aged mountain ash (*Eucalyptus regnans* F. Muell.) growing on loam-type soils of volcanic origin, on rolling hills west of Rotorua in the central north island of New Zealand (Bathgate *et al.*, 1993).

Eleven-year-old stands of fast growing mountain ash with highly variable growth were site-mapped intensively. The objective was to study microsite effects on individual tree growth (a

microsite is defined in terms of the local physical and biological environment in close proximity of an individual tree, similar to the geographical analogy between site and stand). The background for this study was an increasing incidence of dieback in mountain ash, scattered, but widespread and without an identified primary pathogen. This combination suggested that previously unnoticed site properties could trigger or contribute to the dieback process.

An unusually detailed recording of site and stand properties demonstrated that growth, and thus site productivity at the microsite level, in this case related to the relative position and magnitude of different soil horizons below a disturbed A-horizon. A series of volcanic eruptions led to soils with a multi-storied profile, with an older, relatively fertile subsoil buried under topsoil of more recent origin. The fertility of the topsoil is negatively correlated with its thickness. Where the undisturbed part of the topsoil is thicker than 50 cm individual tree growth deteriorates and becomes more variable than where the topsoil is shallower.

The size, shape and distribution of microsite types in this example vary considerably at small as well as large scale, creating mosaics of intimately mixed conditions for tree growth. In addition to this, the study demonstrated that other factors also contribute to variation in growth performance. So, although very simple in principle, this example illustrates some of the practical problems with site mapping and sampling trees for site productivity estimation and, in turn, the cost-benefit considerations that should precede and accompany forest inventory activities.

Maritime pine on coastal dunes in Western Australia

The third example deals with even-aged maritime pine (*Pinus pinaster* Ait.) growing on dune sand at Gnangara, located on the Swan Coastal Plain just north of Perth, Western Australia (Havel, 1968, 2000). The Mediterranean climate with wet winters

and dry summers means that growth is limited by moisture deficits during the summer months.

Figure 2 shows a schematic profile of 45 year old, even-aged maritime pine stand on a dune slope in Gnangara plantation. The slope represents the transition between two successive stages of aeolian depositions, the oldest deposited over 600 000 years ago, the younger 6000–15 000 years ago. Both dune systems originally consisted of highly calcareous beach sand, but are now leached to different degrees (due to age differences). The sand of the oldest dune system contains less iron and phosphorous than the younger sand and is more acidic.

Inspection revealed a continuous gradient in tree height from the oldest dune system on the flat up through the slope to the dune crest where there is an abrupt change in tree height. Neither topography nor soil surface appearance indicates the presence of a site productivity gradient or the discontinuity in that gradient. The slope itself is dominated by sand believed to have been originally deposited at the top of the younger dune, weathered and subsequently re-deposited downhill, thus exposing a better, less weathered substrate for growth at the dune top. In addition to (and in part because of) different degrees of leaching, the two dune systems differ in terms of moisture regime. Owing to a higher colloidal content, the soil moisture capacity is higher on the younger dune at the crest. In the older dune system on the flat, tree growth is more dependent on roots reaching the ground water level.

As a consequence, site productivity is higher in the younger dune system than in the old. The gradient in site productivity on the transition between the two dune systems is related to a gradient in the depth to ground water. The presence of a few indicator plants at this stage of stand development (in 2000) was consistent with these topographical differences in site conditions.

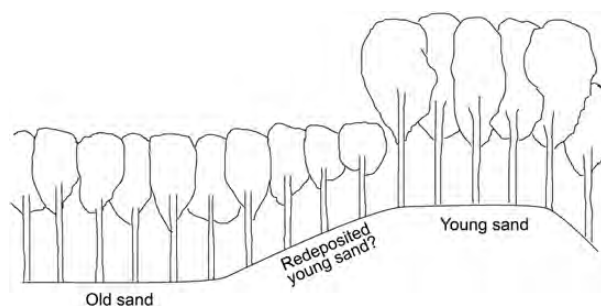


Figure 2 Maritime pine on coastal dune sand in Western Australia (based on Havel, 1968, 2000 and authors' own observations). The slope represents the transition between two successive stages of aeolian deposits. Young sand was re-deposited downhill, exposing at the dune crest a better, less weathered substrate for tree growth with a higher moisture capacity. The gradient in site productivity on the slope is related to a gradient in the depth to ground water. Note that the horizontal and vertical scales are not identical.

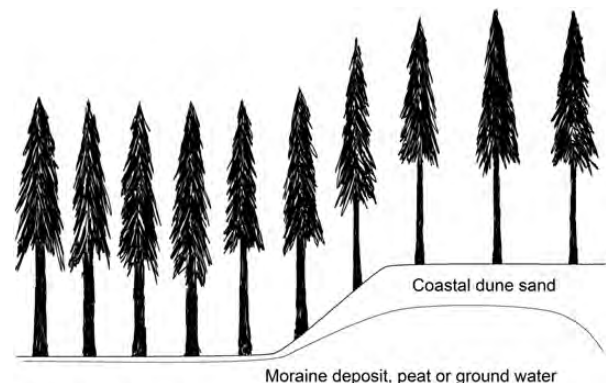


Figure 3 Sitka spruce on coastal dune sand in Denmark (based on Skovsgaard, 1997a,b). A schematic profile of an even-aged stand located on shifting sand over a more fertile subsoil or a subsoil with a higher water holding capacity. Site productivity depends on sand depth, but height growth does not. The example illustrates an unthinned stand at age 45 years. Stand height is 20 m, basal area ranges from 77 m²/ha (left) to 44 m²/ha (right), and the stand density index (reflecting stem number when quadratic mean diameter equals 25 cm) from 1600 per ha (left) to 900 per ha (right). Note that the horizontal and vertical scales are not identical.

Sitka spruce on coastal dunes in Denmark

The fourth example deals with even-aged Sitka spruce (*Picea sitchensis* (Bong.) Carr.) growing on coastal dune sand in plantations along the west and northwest coast of Denmark (Henriksen, 1951, 1958, 1961; Thaarup, 1953; Rasmussen, 1971; Jensen, 1974; Skovsgaard, 1997a,b, 2009). The climate is temperate with mild winters and cool summers. Precipitation falls throughout the year with an annual average of 750 mm.

Figure 3 shows a schematic profile of an even-aged Sitka spruce stand located on a sandburied moraine with sandy clayey soil overlaid by shifting sand. In this example, the sand arrived during recurring periods of sand migration during the Holocene, with the most recent major sand drifts occurring 100–700 years ago.

The point in this example is that height growth during most of the rotation, and most notably early height growth does not depend on sand depth, but basal area production does. The fertile, moisture-holding subsoil provides for a very high basal area production if (and when) the roots reach that substrate.

For even-aged Sitka spruce, the variation in basal area production may be considerable. For example, unthinned stands at a height of 20 m and age 45 years may have a stand basal area ranging from 77 m²/ha on sandburied moraine to 44 m²/ha on dune sites without a subsoil or ground water within reach of the roots. This does not appear to be due to the effect of wind exposure on height growth. Compared with moraine sites that are not covered by dune sand, basal area growth is probably reinforced by the presence of a thin layer of sand. This layer may help prevent evaporation of water from further below ground and thus help maintain a good water supply for the trees at all times.

This example may be expanded to other dune site types in the region. The moraine may be flat with an undulating dune topography on top or the moraine itself may undulate, either in phase with the dune sand (as in Figure 3) or out of phase with the dune sand, creating a more complex variability in soil conditions. Alternatively, the substrata may consist of peat, often in narrow strips parallel to the coastline and interspersed with narrow, slightly higher ridges of sand and gravel.

The occurrence of gradual or abrupt transitions in site productivity depends on the presence of dune sand in relation to the subsoil or ground water as well as the type and variability of subsoil. Owing to the possible complexity in this pattern, site productivity may vary greatly over short distances and with little visible indication of any variation in topography. Ground vegetation is essentially absent in this type of forest. Detailed topographic and soil mapping may offer some insight into the variation in site productivity but is often prohibitively expensive for operational use. Estimation of site productivity may be further confounded by site-dependent effects of thinning on the stand volume growth of Sitka spruce (Skovsgaard, 2009).

Natural satinay forests on coastal dunes in Queensland, Australia

While our first four examples draw on experience with exotic tree species that are managed under a plantation philosophy, similar situations of short-range variability in site productivity can be found in natural forests. Our own observations of natural forests of satinay (*Syncarpia hillii* F.M. Bailey) growing on

coastal dunes in the Cooloola region and on Fraser Island in Queensland, Australia serve as an example.

In this region, the climate is maritime subtropical with mild winters and distinctively seasonal rainfall. Annual precipitation averages 1500–1775 mm. Cooloola and Fraser Island consist almost entirely of sand. Throughout the region dunes of oceanic sands occur over older sands with a higher content of silt and clay. Successive, physically more-or-less overlapping dune systems provide a range of different site conditions, depending on age of the dune system, exposure to wind, depth to older sand, etc. (Thompson, 1981, 1983, 1992; Grimes, 1992; Walker *et al.*, 1981, 2001). Over time, deep podzol profiles have developed in these dunes.

Although they are no longer managed for timber production, some of the satinay forests have been logged in the past. Now, stands are often essentially even-aged, monospecific or mixed with brush box (*Lophostemon confertus* (R. Br.) P.G. Wilson & Waterhouse) and kauri pine (*Agathis robusta* (C. Moore ex F. Muell.) F.M. Bailey) of apparently similar age.

Sheltered parts of early Holocene origin, especially in valleys, provide conditions that support large trees and high standing volumes, while other, more exposed and younger parts of the dune systems support less lush stands of similar species composition. Here, the transition from one set of site conditions to the other often occurs within a short distance, for example, near the crest of a dune. In this example, variations in site productivity are related to a combination of many factors, including lee from the wind, accumulation of litter and nutrients, the potential for a deep development of roots for continuous supply of water and possibly nutrients from deeply situated soil horizons, etc.

Implications

The five examples of spatial variability in site conditions all represent site and stand types of considerable local or national distribution and importance. These examples have been selected for their instructive utility in production forestry, but many other examples exist ranging from tropical mangroves (Ferreira *et al.*, 2010) to boreal conifers (Lavoie *et al.*, 2009). Collectively, the examples demonstrate the need to consider carefully any possible variations in site productivity, especially in routine inventories that may not be designed to detect previously unnoticed variation in site and stand conditions, and in plantation or plantation-like forests characterized by extensive monospecific even-aged stands established without regard to site variation. In large-scale inventories, site variations and transitions may remain undetected unless the inventory embraces site mapping or measures tree and stand characteristics that accurately reflect the three-dimensional nature of stand volume growth. Some of the examples also demonstrate the need to consider site-specific indicators of site productivity or site-specific estimation procedures.

Temporal variability in productivity

Though we commonly assume it to be constant, at least during one rotation of a tree crop, site productivity may vary over time. Both the site productivity *per se*, and the indicators that we commonly use, may vary. Temporal variability in productivity may be due to management effects, species-specific natural growth

patterns, seasonality or other factors in the environment. Here, we present six examples to illustrate the problems that may occur when estimating site productivity in such situations.

Growth patterns

With even-aged stands the very nature of forest growth prevents a full utilization of the site potential at all times, particularly in young stands. Current and mean annual increment of above-ground wood volume are well-established measures of site productivity and develop along a well-known pattern which illustrates that young stands only partially utilize a site. Other variables such as net primary production and the increment of total tree biomass or merchantable volume may follow different trajectories and may indicate a slightly different site utilization.

Because forestry is concerned with the wood volume that can be realized, the maximum mean annual volume increment is considered a more convenient measure of site productivity

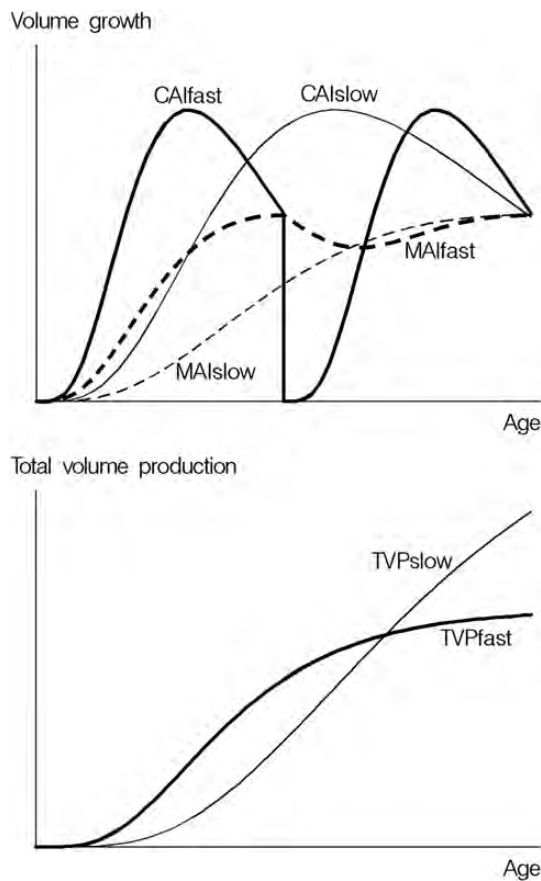


Figure 4 Mean annual increment as a measure of forest site productivity. This figure illustrates two hypothetical species, a fast-growing short-rotation species (cf. a tropical acacia (*Acacia* sp.) or eucalypt (*Eucalyptus* sp.)), and a slow-growing long-rotation species with a higher yield asymptote (cf. a temperate, late-successional species such as European beech (*Fagus sylvatica* L.)). Two rotations of the former may have an average mean annual increment (top) similar to that of the latter species. Species may have very different yield curves (bottom), but still exhibit the same mean annual increment. Legend: CAI, current annual increment; MAI, mean annual increment, TVP, total volume production.

than the instantaneous production represented by current annual increment or maximum current annual increment.

The time at which mean annual volume increment culminates depends on site, species and silvicultural regime. Several rotations of pulpwood production in the tropics may be achieved in the time taken to yield a single sawlog rotation in a temperate region, but maximum mean annual increment should still offer a suitable basis for comparison, even though final harvest volumes may differ markedly (Figure 4). Comparisons should be straightforward when successive rotations follow immediately, but assumptions should be clearly stated when subsequent rotations are interspersed with a fallow period, or when shelterwood systems allow overlapping rotations.

Changes in allometric relations with age

Temporal changes in allometric relations may impinge on the suitability of site productivity indicators, partly because the relation between variables deteriorate or even reverse, partly because of mensuration problems.

For example, tree height growth tends to be rapid for young trees, gradually diminishes and sometimes even ceases when trees age. In contrast basal area growth may be slow initially, but may continue long after net height growth becomes imperceptible. This is obviously the case on coastal sites, where strong winds can ‘prune’ the tops of trees even in closed stands, but may also occur on more sheltered sites.

If height growth diminishes significantly within the normal rotation period, this may hamper the estimation of site index in old stands and impede the prediction of volume growth (Figure 5), especially if predictions rely on height (the principle of Eichhorn’s rule). The phenomenon is known for many species and locations, for example, Scots pine (*Pinus silvestris* L.) in Europe and karri (*Eucalyptus diversicolor* F. Muell.) in Western Australia. This is of practical significance for Scots pine on poor sites where rotations

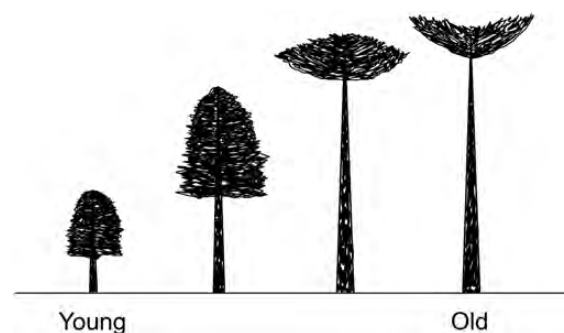


Figure 5 Age-dependent changes in allometric relations. If height growth diminishes significantly within the normal rotation period, this may hamper the estimation of site index in old stands and impede the prediction of volume growth, especially if predictions rely on height (the principle of Eichhorn’s rule). Depending on diameter growth and management practice, stand basal area may be used as an additional indicator of productivity. Note that the horizontal and vertical scales are not identical.

tend to be prolonged, whereas managed karri stands are generally regenerated before the problem occurs.

A more subtle, but conspicuous variant of this problem occurs with the genus *Araucaria*, and is illustrated with Parana pine (*Araucaria angustifolia* (Bert.) O. Ktze.) in Brazil, where tip growth slows down before lateral branch growth (Seitz, 1986). Trees with parabolic-shaped crowns respond to release with increased basal area growth, whereas individuals with saucer-shaped crowns no longer respond to thinning (Figure 5). In this case, the estimation of site productivity is hampered for two reasons: in the first place because height growth slows down relative to basal area growth, in the second place because height becomes very difficult to measure. The latter problem also applies to silver fir (*Abies alba* Mill.) in Europe and mountain ash (*Eucalyptus regnans* F. Muell.) in Australia due to dieback of the leader shoot and top branches in old stands. If stands become old enough this could be a potential problem with any tree species.

As a consequence, the relative suitability of forest site productivity indicators may change with the age of the stand.

Seasonal variability in productivity

Climates with a distinct seasonal pattern obviously may lead to seasonal variability in forest growth and productivity. Owing to the scale of resolution used for time, seasonal growth patterns are usually not considered when assessing site productivity, because we integrate across the seasonality (most commonly in one year time steps). However, such seasonality may have a considerable influence on stand production and on silvicultural options to enhance it.

For example, the growth of radiata pine (*Pinus radiata* D. Don) in South Australia is strongly limited by water supply during the warm and dry summer months (Figure 6), partially because of the climatic conditions, partially because of lack of ground water. Theoretical calculations have demonstrated that if rainfall were not a limiting factor, volume growth could be doubled

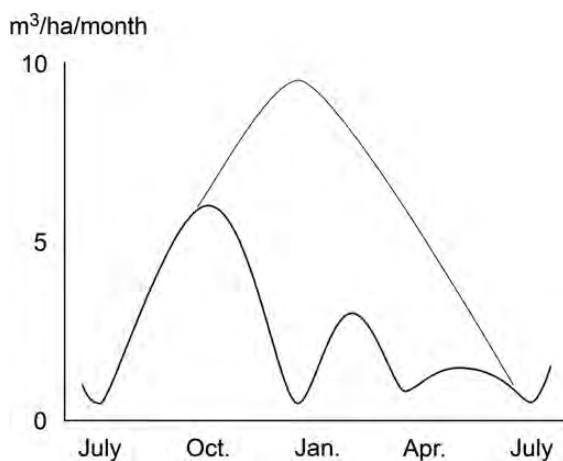


Figure 6 Seasonal variability in productivity of radiata pine for a site in South Australia (based on Boardman, 1988). The site is subject to winter rainfall and seasonal soil moisture deficit. Theoretical calculations (thin line) demonstrate that if rainfall were not a limiting factor, volume growth could be doubled. Had irrigation been practically and economically possible, this would challenge the definition of site potential for stand volume growth.

(Boardman, 1988). Had irrigation been practically and economically feasible, this would challenge the definition of site potential for stand volume growth. This interaction between management and site productivity warrants further research.

In addition to annual patterns in productivity, perturbations may occur at longer or irregular intervals, for example, due to drought, flooding, storm damage, ice breakage, attacks by insects, fungi etc.

Apparent site change

Some dendrometric indicators may suggest temporal changes in site productivity, when no site change is evident. This may occur if the plant utilizes different parts of the substrate as the roots develop or if one or more environmental factors interfere with the 'normal' growth pattern. For example, when the topsoil is shallow or when browsing or adverse climatic conditions hamper height development, early growth may not be a reliable indicator of long-term growth.

A plantation of Caribbean pine (*Pinus caribaea* Morelet) at Wongi near Maryborough in Queensland, Australia offers an example of this effect. During the 1980s, the Queensland Department of Forestry used intensive site preparation, including the formation of mounds on seasonally waterlogged sites like the Wongi plantation (Francis, 1983). As a result, early growth of this plantation was promising, but once the soil within the mound was fully occupied and the crop began to utilize the poorer subsoil below, growth began to slow down relative to the expectation (Figure 7).

Comparable effects occur in plantations of Norway spruce (*Picea abies* (L.) Karst.) on sites where frost or browsing by deer retards height growth, for example, in Denmark (Nord-Larsen *et al.*, 2009). In this case, however, early height growth would underestimate long-term site productivity. When wind exposure reduces early growth, such as for sycamore (*Acer pseudoplatanus* L.) and European ash (*Fraxinus excelsior* L.) on lowland sites in Great Britain (Willoughby *et al.*, 2009), productivity estimates obviously depend strongly on the future development of wind exposure.

Under extreme climatic conditions (Rottmann, 1985, 1986; Mayer, 1992; Kraemer and Nyland, 2010) and at high elevation (Mayer, 1976) recurring damage to tops of upper-canopy trees due to wind, ice or snow may similarly invalidate the use of unadjusted height-age relationships for estimating site productivity. While snow breakage most frequently occur on the smaller trees in a stand, wind and the combined effects of wind and ice glaze most frequently hit the larger trees commonly used in site productivity assessments.

Deviant growth patterns of this kind require local growth models or adjustments of more general models. Once a departure from the general growth model is observed, growth intercept methods (e.g. Wakeley, 1954; Economou, 1990) or other 'age-shift' methods (e.g. South *et al.*, 2006; Carlson *et al.*, 2008) may provide a more reliable indication of long-term growth, as they reveal the current performance rather than average growth to date.

Apparent site change for Sitka spruce in Denmark

Our next example deals with even-aged Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Denmark (Henriksen, 1958; Skovsgaard, 1997a,b, 2009). Four site types with distinctively different growth patterns are recognized and are attributed mainly to differences

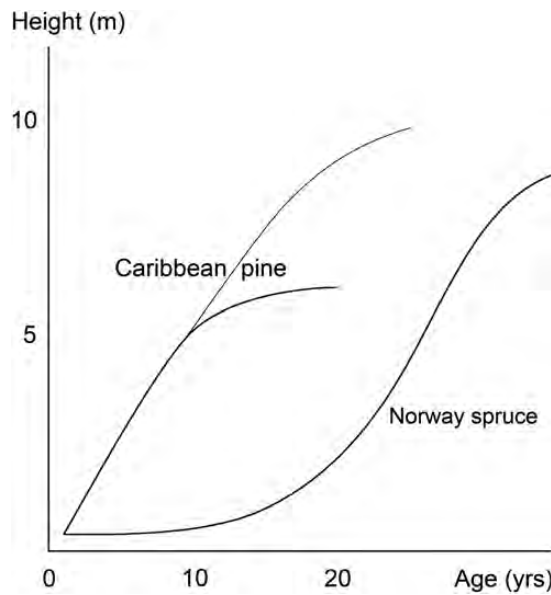


Figure 7 Apparent site change. Growth patterns (unpublished data) of a plantation of Caribbean pine at Wongi near Maryborough in Queensland, Australia, and of Norway spruce on heathland in the western part of Denmark. The Caribbean pine was established by mounding on seasonally waterlogged sites. Early growth was promising, but once the soil within the mound was fully occupied and the crop began to utilize the poorer subsoil below, growth began to slow down (thick line) relative to trial plots on better sites (thin line). The early growth of Norway spruce was hampered by late frost and browsing, which is a general problem in this region. Gradually, the trees outgrew the obstacles. A vigorous root development and the successively improved within-stand shelter provide for a dramatic change in growth pattern.

in soil conditions (Figure 8). Large variations in total volume production for a given stand height and age occur across site types.

Two site types with the most straightforward growth pattern include coastal dune sand without a more fertile subsoil or ground water within reach of the roots (yield level L), and different types of glacial till moraine (M). Two other coastal site types, a sandburied moraine (H) and a raised littoral seabed with a high and fluctuating groundwater table (S), presented more complex growth patterns. For the latter two, height growth may be more-or-less uncorrelated with volume growth.

Skovsgaard (1997a) found that a stand density index expressed as a simple, three-dimensional indicator of site productivity (Sterba, 1987) could not unambiguously characterize site-specific yield levels for Sitka spruce on coastal sands in Denmark using only mensurational stand characteristics (Figure 9).

The problem in this case is that the site potential changes with stand development, more specifically with root development. As roots gradually penetrate the dune or beach sand and reach better and more persistent water supply site productivity concurrently increases tremendously (Figures 3, 8 and 9 collectively illustrate this point). Despite early growth literally at the low end of the scale, sandburied moraine (H) produces the highest volume yields on record in Denmark, provided the sand is not too deep. The volume growth on sandy sites with a high groundwater table (S) may eventually level off, again changing growth pattern as compared to other site types. Where

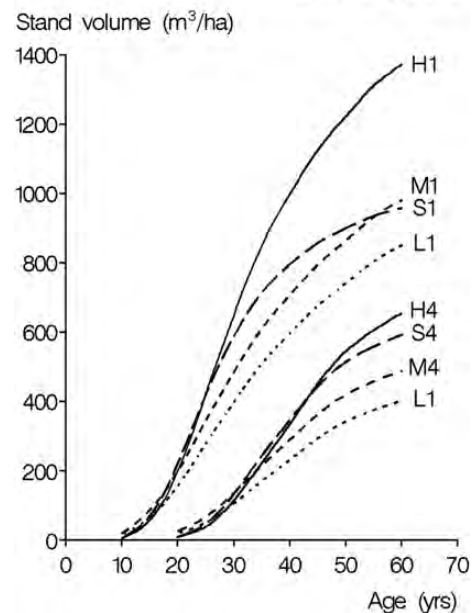
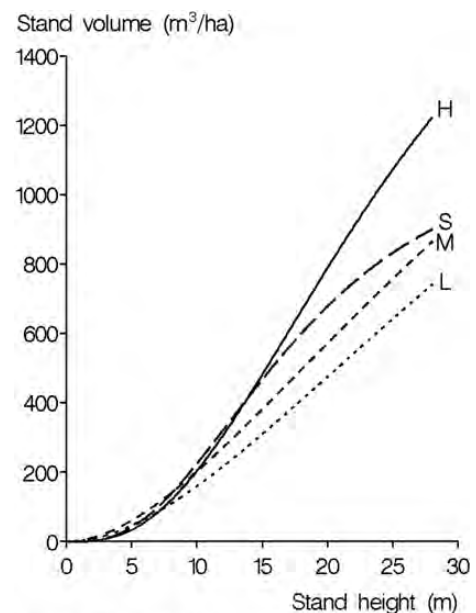


Figure 8 Site-specific levels of stand volume versus height (top) and age (bottom) for even-aged, unthinned Sitka spruce in Denmark (based on Skovsgaard, 1997a). For unthinned stands, stand volume is a suitable indicator of yield level. Four different site types have different yield levels (top), for which height growth may vary considerably (yield level H = high, S = high, but stagnant, M = medium, L = low). The volume produced at a given age (bottom) depends on both yield level and site class (site class 1: height = 28 m at age 50 years from seed, 4: height = 16 m at age 50 years). The combinations of a high yield level and a low site class, or vice versa, may be unrealistic, but are included to illustrate principles more clearly.

fluctuating ground water is present near the root zone, the site potential may depend on the interaction between water availability and water requirements. This, in turn, depends on age and stand density (Skovsgaard, 1997a,b, 2009).

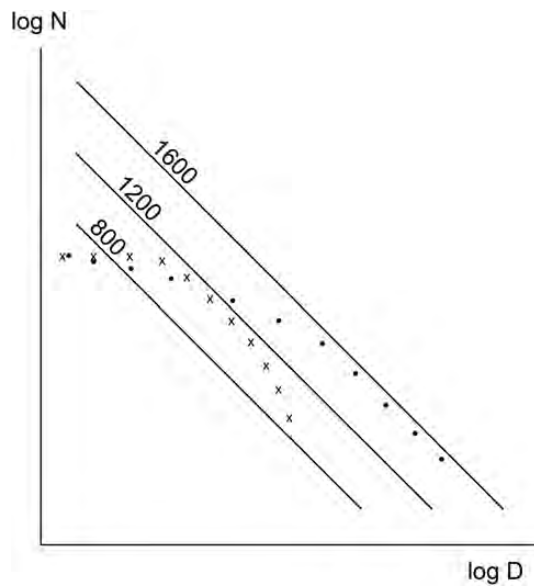


Figure 9 Apparent site change for unthinned Sitka spruce on coastal sands in Denmark (based on Skovsgaard, 1997a). Stand density index lines (from 800 to 1600 trees per ha at a quadratic mean diameter of 25 cm) correspond to the regional range in the site-specific yield level. For one site type (dots) site productivity increases with root development due to a subsoil with higher fertility and stable water supply (sandburied moraine). For another site type (crosses) site productivity levels off at old age due to water balance problems (deep sand with fluctuating ground water).

This example demonstrates that in some situations it is impossible to classify site types or predict long-term growth using only mensurational stand and tree characteristics. Even if the site type and its specific growth pattern are known, predictions may be inaccurate or imprecise due to unpredictable variations in site conditions. The four site-stand combinations presented here develop along different, non-proportional and overlapping trajectories, even in the absence of externally imposed environmental changes.

Real changes in site conditions

Although changes in growth often can be attributed to changes in the interaction between stand and site, as in the examples above, site change *per se* does occur. Several tree species and management practices may temporarily or permanently modify site conditions, for example, soil fertility, soil pH, humus, mycorrhiza, soil physical structure or ground water table (e.g. Burger, 2004; Morris, 2004; Torreano, 2004; Weiler and McDonnell, 2004).

There may also be more subtle changes in site productivity that can be detected only in the longer term (e.g. Sterba, 1995; Spiecker *et al.*, 1996; Valentine, 1997; O'Hehir and Nambiar, 2010). Such changes could be caused, in part, by off-site anthropogenic factors such as atmospheric deposition of nitrogen and other nutrients, or by climatic change (e.g. Boisvenue and Running, 2006; Messaoud and Chen, 2011).

Gradual environmental changes inevitably confound with the age-related growth pattern of forest trees (Figure 10). If long-term data for a wide range of ages are available, these effects may be separated analytically. The quantification of temporal

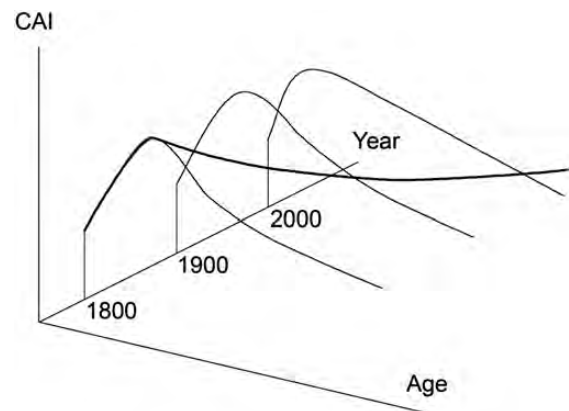


Figure 10 Temporal changes in productivity (CAI = current annual increment). When monitoring and predicting forest growth (thick line), environmental change is bound to confound with the age-related growth pattern (thin lines). If long-term data for a wide range of ages are available, these effects may be separated analytically.

changes in growth pattern may provide insight into the effects of environmental change on forest dynamics. However, predictions for the future will always have to rely on information on the past and present.

Implications

Our examples of temporal variability in forest productivity illustrate that forest researchers and managers should be aware of potential variations in site conditions. Plantation developments in new situations, where growth trends have not been empirically established, should be carefully monitored. If a departure from the expected growth trend is suspected, assessment methods based on periodic increment (e.g. the height intercept approach) may be more revealing than methods based on cumulative performance (e.g. estimates based on the height-age relationship). Possible site changes *per se*, related to management or other factors, may confound with these effects and, if significant, should be taken into account.

Discussion

Site index, one of the most widely used indicators of wood production, is undoubtedly useful in both forest research and management. However, our examples demonstrate that the site index (and other uni-dimensional estimators) is not always sufficient to characterize site productivity for apparently homogeneous forest stands. Clearly, the reliability of site productivity estimates may be improved by accounting for spatial as well as temporal variation in natural site conditions.

Spatial variability in site conditions

Efficient management requires reliable resource information and forecasts, which in turn depend on accurate site productivity assessments. Any discontinuity or heterogeneity in site conditions may compromise the reliability of forecasts and the efficiency of operations and experiments. Site discontinuities also represent a major challenge for forest inventory.

Consequently, we advocate site mapping, even for apparently homogeneous land areas, and even where stand conditions do not seem to vary significantly. The level and detail at which site mapping should be conducted (region, forest, management unit or subunit), depends on the objective (research vs. operational forestry), forest type and expected deviations in site productivity estimates compared with the cost of site mapping. Recent developments with lidar offer potential for efficient 'wall-to-wall' site mapping (Næsset, 2004; Andersen *et al.*, 2005). Certainly, this should enhance the understanding of response patterns and provide a frame for suitable stratification of sampling efforts.

Because of practical implications of spatial and temporal variability in productivity, we recommend that unthinned reference plots (Assmann, 1961, 1970; Skovsgaard and Vanclay, 2008) be established and maintained as routine practice, to establish the local site-specific potentials for forest growth, ensure accurate growth predictions and enable sustainable harvest levels to be estimated. Relatively few plots are needed, depending on the homogeneity of the soil, topography and microclimate.

For very homogeneous land, the logarithm of the estate area (one plot in 10 ha; two in 100 ha, etc.) may serve as a general guide, but more plots will be required in heterogeneous situations, where it is instructive to monitor extremes as well as prevailing site and stand conditions (Vanclay *et al.*, 1995). These plots should be viewed as a long-term commitment to offer insights into long-term site dynamics. A few plots that are re-measured regularly and maintained in the long term are likely to offer greater insights than a larger number of plots measured infrequently or in the short term.

Temporal manifestation of site productivity

The temporal manifestation of site productivity is often thought of in terms of chronological time. Hence, time is considered at an equidistant, linear scale. This may be a limitation where, for example, the site potential changes with stand development, in which case an identical temporal scale across site conditions may lead to flawed interpretations. In contrast, in his state-space approach, García (1994) assumed that the 'clock' would run faster on better sites, with better stands attaining all stages of development more rapidly.

Often, stand height is used as a substitute for age or time. However, for some aspects or stages of stand development, height may not be a suitable substitute. This could be due to the ageing of apical meristems, the age distribution of foliage (evergreen trees), ring width, the accumulative nature of volume growth (for individual trees) or the quantity of photosynthetically active foliage. All of these factors may depend on age.

Finally, the interaction between factors that determine site productivity, including silviculture and other management activities, may change over time. Consequently, the site-specific relationships between age, stand height, volume growth and other dendrometric variables, would depend on other factors than those inherent to site and species. To our knowledge this has not been investigated, but could be an outcome of the effects of global change on forest growth.

Site productivity in meta-perspective

It is unlikely that there will ever be a universal definition of forest site productivity. Any definition will depend on the purpose of

estimating site productivity, and cannot be divorced from that purpose.

In our discussion, we have focused on the timber production potential, i.e. the production of aboveground wood volume, and have excluded approaches reliant on dry matter production or including leaves, needles and roots. For broadleaved tree species, the definition of aboveground volume often includes branchwood, whereas branchwood is usually excluded for conifers.

Our site productivity is thus incomplete or partial, because it only deals with part of the realized or potential productivity. A consequence of this may be, for example, that the productivity of conifers on infertile land may be underestimated in terms of aboveground dry matter production, compared with the productivity of the same species on more fertile land.

Ultimately, the estimation of site productivity is about carrying capacity at a given stage of stand development. A site's carrying capacity for wood production may be dynamic and may vary at different times during a rotation. In turn, it reflects the site factors limiting tree growth.

Forest site productivity can be defined in relation to spatial and temporal dimensions as well as management practices. Clearly, current concepts of site productivity do not agree entirely with all facts, but documenting the strengths and weaknesses of these concepts provide a sound basis for further development.

Conclusion and recommendations

In the context of site productivity estimation, the objective of site mapping is to account for variation in site conditions which may influence productivity estimates or the estimation procedure. Even with apparently homogeneous land areas in which stand conditions do not seem to vary significantly, site mapping may confirm or invalidate such assumptions.

As an additional aid for practical forestry as well as for research, we recommend establishing and maintaining unthinned observation plots in managed forests. These may serve as a reference against which to measure growth performance. With the passage of time, such plots may also provide valuable indications of the effects of environmental change on forest dynamics, and of possible long-term changes in the relationship between estimators of site productivity and tree and stand characteristics. The percentage of reference plots should increase with increasing site or stand heterogeneity.

In summary, some of the problems with spatial and temporal perturbations in forest site productivity may be difficult to solve completely. This holds for inventory as well as for modelling procedures. We therefore recommend adaptive modelling. With adaptive modelling site specific parameters can be updated at any time when new information has become available. This will help ensure efficient use of relevant information, including possible changes in site productivity and growth performance.

Acknowledgements

The examples in this paper were collected during 35 years of our professional career in forest research and forestry practice. Several colleagues and friends contributed to this endeavour, sometimes even without knowing to do so, and family members endured site productivity discussions that often may have seemed endless. They are too many to

mention individually, and with the passage of time the origin of some contributions may even have vanished. We extend our sincere thanks to all who contributed or helped in one way or the other.

Conflict of interest statement

None declared.

Funding

Formative development of this paper took place 1999–2000, 2005 and 2010 during the senior author's sabbaticals at Southern Cross University, Australia. The first sabbatical was supported by the Danish Agricultural and Veterinary Research Council (grant no. 9901207), Carlsen-Lange's Foundation, and Vemmetofte Aristocratic Convent. The second sabbatical was supported by O.H.F. and A.J.-E. Heilmann's Foundation. During 1987–2000 additional support was received from Chamberlain, Master of the Royal Hunt, Chief Forest Supervisor Frederik Carl Eide's and Mrs Christine Elisabeth Eide, née Sarauw's Foundation for the benefit of widows of forest supervisors, subordinate forestry officials and the advancement of forestry (1987, 1990, 2000), The Forestry Travel Fund of the Royal Veterinary and Agricultural University in Copenhagen (1988), Danish Forestry Graduate's Travel Fund (1990), Danish Agricultural Ph.D. Graduates' Study Fund (1993), and Forest Manager Mogens Andersen and Mrs Elin Michaela Andersen's Foundation (2000). Forest & Landscape Denmark at University of Copenhagen, Swedish University of Agricultural Sciences, and the School of Environment, Science and Engineering at Southern Cross University, provided substantial institutional support.

References

- Andersen, H.-E., McGaughey, R.J. and Reutebuch, S.E. 2005 Forest measurement and monitoring using high-resolution airborne lidar. *USDA Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR* **642**, 109–120.
- Assmann, E. 1950 Grundflächen- und Volumenzuwachs der Rotbuche bei verschiedenen Durchforstungsgraden. *Forstwiss. Centralbl.* **69**, 256–286.
- Assmann, E. 1954 Grundflächenhaltung und Zuwachsleistung Bayerischer Fichten-Durchforstungsreihen. *Forstwiss. Centralbl.* **73**, 257–271.
- Assmann, E. 1955 Die Bedeutung des 'erweiterten Eichhorn'schen Gesetzes' für die Konstruktion von Fichten-Ertragstafeln. *Forstwiss. Centralbl.* **74**, 321–330.
- Assmann, E. 1956 Natürlicher Bestockungsgrad und Zuwachs. *Forstwiss. Centralbl.* **75**, 257–265.
- Assmann, E. 1959 Höhenbonität und wirkliche Ertragsleistung. *Forstwiss. Centralbl.* **78**, 1–20.
- Assmann, E. 1961 *Waldertragskunde. Organische Produktion, Struktur, Zuwachs und Ertrag von Waldbeständen*. BLV Verlagsgesellschaft, München, Bonn, Wien. XV + 490 pp.
- Assmann, E. 1970 *The Principles of Forest Yield Study. Studies in the Organic Production, Structure, Increment and Yield of Forest Stands*. Pergamon Press, Oxford. etc. XIV + 506 pp.
- Avery, T.E. and Burkhardt, H.E. 2002 *Forest Measurements*, 5th edn. McGraw Hill, Boston. etc. XX + 456 pp.
- Bathgate, J.L., Guo, L.B., Allbrook, R.F. and Payn, T.W. 1993 Microsite effect on *Eucalyptus regnans* growth. *New Zeal. J. For. Sci.* **23**, 154–162.
- Baur, F. 1877 *Die Fichte in Bezug auf Ertrag, Zuwachs und Form*. Verlag von Julius Springer, Berlin. IV + 104 pp. + 7 lithographirten Tafeln.
- Boardman, R. 1988 Living on the edge—the development of silviculture in South Australian pine plantations. *Aust. Forestry* **51**, 135–156.
- Boisvenue, C. and Running, S.W. 2006 Impacts of climate change on natural forest productivity—evidence since the middle of the 20th century. *Glob. Change Biol.* **12**, 862–882.
- Burger, J.A. 2004 Soil and its relationship to forest productivity and health. *Encyclop. For. Sci.* **3**, 1189–1195.
- Burkhardt, H.E. and Tomé, M. 2012 *Modelling Forest Trees and Stands*. Springer, Dordrecht etc. XIV + 457 pp.
- Carlson, C.A., Fox, T.R., Allen, H.L. and Albaugh, T.J. 2008 Modeling mid-rotation fertilizer responses using the age-shift approach. *For. Ecol. Manage.* **256**, 256–262.
- Economou, A. 1990 Growth intercept as an indicator of site quality for planted and natural stands of *Pinus nigra* var. *pallasiana* in Greece. *For. Ecol. Manage.* **32**, 103–115.
- Eichhorn, F. 1902 *Ertragstafeln für die Weistanne*. Verlag von Julius Springer, VII + 81 pp. + Anhang.
- Eichhorn, F. 1904 Beziehungen zwischen Bestandshöhe und Bestandsmasse. *Allg. Forst- Jagdztg.* **80**, 45–49.
- Ferreira, F.O., Otero, X.L., de Souza, V.S. Jr, Vidal-Torrado, P., Macias, F. and Firme, L.P. 2010 Spatial patterns of soil attributes and components in a mangrove system in southeast Brazil (Sao Paulo). *J. Soil. Sediment.* **10**, 995–1006.
- Francis, P.J. 1983 Growth of Exotic Pine on Wongi State Forest. *Department of Forestry, Queensland, Unpublished Report No. 12*. 20 pp. + app.
- García, O. 1994 The state-space approach in growth modelling. *Can. J. Forest Res.* **24**, 1894–1903.
- Gehrhart. 1909 Ueber Bestandes-Wachstumsgesetze und ihre Anwendung zur Aufstellung von Ertragstafeln. *Allg. Forst- Jagdztg.* **85**, 117–128 + Anhang.
- Gehrhart. 1921 Eine neue Kiefern-Ertragstafel. *Allg. Forst- Jagdztg.* **97**, 145–156.
- Grimes, K.G. 1992 Fraser Island, Queensland. *Department of Resource Industries, Geological Survey of Queensland, 1:250,000 Geological Series - Explanatory Notes: Sheet SG 56-3*. IV + 39 pp. + maps.
- Havel, J.J. 1968 The potential of the northern Swan coastal plain for *Pinus pinaster* Ait. plantations. *W.A. Forests Department Bulletin* No. 76. Reprint 1976, 73 pp.
- Havel, J.J. 2000 *Personal communication during and after a field trip to Gngangara plantation, Western Australia, in March 2000*.
- Henriksen, H.A. 1951 Et udhugningsforsøg i sitkagran. *Det forstlige Forsøgsvæs. Dan.* **20**, 403–418.
- Henriksen, H.A. 1958 Sitkagranens vækst og sundhedstilstand i Danmark. *Det forstlige Forsøgsvæs. Dan.* **24**, 1–372.
- Henriksen, H.A. 1961 A thinning experiment with Sitka spruce in Nystrup dune forest. *Det forstlige Forsøgsvæs. Dan.* **27**, 169–232.
- Heyer, C. 1841 *Die Waldertrags-Regelung*. Verlag von B.C. Ferber, Giesen. VIII + 264 pp.
- Husch, B., Beers, T.W. and Kershaw, J.A. 2003 *Forest Mensuration*, 4th edn. Wiley, Hoboken, NJ. XII + 443 pp.
- Jensen, A.M. 1974 Soil and forest protection with special reference to sand dunes. In: *Report on the FAO/DANIDA inter-regional training centre on heathland and sand dune afforestation, Denmark and Libya, 26 August - 21 September 1973*. Food and Agriculture Organization of the United Nations, Rome. X + 239 pp.
- Kraemer, M.J. and Nyland, R.D. 2010 Hardwood crown injuries and rebuilding following ice storms: a literature review. *USDA Forest Service, Northern Research Station, General Technical Report NRS*, **60**, 1–29.
- Langsæter, A. 1941 Om tynning i enaldret gran- og furuskog. *Medd. Nor. Skogforsøksves.* **8**, 131–216.

- Lavoie, M., Harper, K., Pare, D. and Bergeron, Y. 2009 Spatial pattern in the organic layer and tree growth: A case study from regenerating *Picea mariana* stands prone to paludification. *J. Veg. Sci.* **18**, 213–222.
- Mayer, H. 1976 *Gebirgswaldbau - Schutzwaldpflege*. Gustav Fischer, Stuttgart. XX + 436 pp.
- Mayer, H. 1992 *Waldbau auf soziologisch-ökologischer Grundlage*, 4th edn. Gustav Fischer, Stuttgart, Jena, New York. XXV + 522 pp.
- Meredieu, C., Arrouays, D., Goulard, M. and Auclair, D. 1996 Short range soil variability and its effect on red oak growth (*Quercus rubra* L.). *Soil Sci.* **161**, 29–38.
- Messaoud, Y. and Chen, H.Y.H. 2011 The influence of recent climate change on tree height growth differs with species and spatial environment. *PLoS ONE* **6**(2), e14691.
- Møller, C.M. 1944 Untersuchungen über Laubmenge, Stoffverlust und Stoffproduktion des Waldes. *Det forstlige Forsøgsvæs. Dan.* **17**, 1–287 + Tabeller.
- Møller, C.M. 1951 *Træmålings- og tilvækstlære*. Den kgl. Veterinær- og Landbohøjskole, København. 6 + 332 pp.
- Møller, C.M. 1954 The influence of thinning on volume increment. I. Results of investigations. *State Univ. N.Y., Coll. For. Syracuse, World For. Ser.* **1**, 5–32.
- Morris, L.A. 2004 Soil organic matter forms and functions. *Encyclop. For. Sci.* **3**, 1201–1207.
- Næsset, E. 2004 Practical large-scale forest stand inventory using a small-footprint airborne scanning laser. *Scand. J. Forest Res.* **19**, 164–179.
- Nord-Larsen, T., Meilby, H. and Skovsgaard, J.P. 2009 Site-specific height growth models for six common tree species in Denmark. *Scand. J. Forest Res.* **24**, 194–204.
- O'Hehir, J.F. and Nambiar, E.K.S. 2010 Productivity of three successive rotations of *P. radiata* plantations in South Australia over a century. *For. Ecol. Manage.* **259**, 1857–1869.
- Philip, M.S. 1994 *Measuring Trees and Forests*, 2nd edn. CAB International, Wallingford. XIV + 310 pp.
- Pretzsch, H. 2009 *Forest Dynamics, Growth and Yield*. Springer, Berlin, Heidelberg. XIX + 664 pp.
- Rasmussen, A.H. 1971 Klitskoven i Thisted Amt med særligt henblik på blandingsskovens muligheder. *Dan. Skovforen. Tidsskr.* **56**, 195–281.
- Rottmann, M. 1985 *Schneebruchschäden in Nadelholzbeständen*. J.D. Sauerländer's Verlag, Frankfurt am Main. V + 159 pp.
- Rottmann, M. 1986 *Wind- und Sturmschäden im Wald*. J.D. Sauerländer's Verlag, Frankfurt am Main. IV + 128 pp.
- Seitz, R.A. 1986 Crown development of *Araucaria angustifolia* in its natural environment during sixty years. In *Crown and Canopy Structure in Relation to Productivity*. Fujimori, T. and Whitehead, D. (eds). 1986 Proceedings, Forestry and Forest Products Research Institute, Ibaraki, Japan, pp. 129–146.
- Skovsgaard, J.P. 1997a Management of Sitka spruce without thinnings. An analysis of stand structure and volume production of unthinned stands of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Denmark. *Forskningscentret for Skov & Landskab, Forskningsserien* **19**, 1–525.
- Skovsgaard, J.P. 1997b *Tyndingsfri drift af sitkagran*. Special issue of *Skoven*, vol. **29**. Forskningscentret for Skov & Landskab & Dansk Skovforening. 40 pp. ISBN 87-89822-83-8.
- Skovsgaard, J.P. 2009 Analysing effects of thinning on stand volume growth in relation to site conditions: a case study for even-aged Sitka spruce (*Picea sitchensis* (Bong.) Carr.). *Forestry* **82**, 87–104.
- Skovsgaard, J.P. and Vanclay, J.K. 2008 Forest site productivity: a review of the evolution of dendrometric concepts for even-aged stands. *Forestry* **81**, 13–31.
- South, D.B., Miller, J.H., Kimberley, M.O. and Vanderschaaf, C.L. 2006 Determining productivity gains from herbaceous vegetation management with 'age-shift' calculations. *Forestry* **79**, 43–56.
- Spiecker, H., Mielikäinen, K., Köhl, M. and Skovsgaard, J.P. (eds). 1996 *Growth Trends of European Forests: Studies from 12 Countries*. Springer Verlag. XI + 372 pp.
- Sterba, H. 1975 Assmanns Theorie der Grundflächenhaltung und die 'competition-density-rule' der Japaner Kira, Ando und Tadaki. *Cent. Gesamte Forstw.* **92**, 46–62.
- Sterba, H. 1981 Natürlicher Bestockungsgrad und Reinekes SDI. 1. Bestandesdichte und Ertragsniveau. *Cent. Gesamte Forstw.* **98**, 101–116.
- Sterba, H. 1985 Das Ertragsniveau und der maximale Stand-Density-Index nach Reineke. *Cent. Gesamte Forstw.* **102**, 78–86.
- Sterba, H. 1987 Estimating potential density from thinning experiments and inventory data. *For. Sci.* **33**, 1022–1034.
- Sterba, H. 1995 Forest decline and increasing increments: a simulation study. *Forestry* **68**, 153–163.
- Thaarup, P. 1953 *Klitplantagerne 100 år efter plantningens begyndelse*. Landbrugsministeriet, Danmark. 96 pp.
- Thompson, C.H. 1981 Podzol chronosequences on coastal dunes of eastern Australia. *Nature* **291**, 59–61.
- Thompson, C.H. 1983 Development and weathering of large parabolic dune systems along the subtropical coast of eastern Australia. *Z. Geomorph., Neue Folge, Suppl.* **45**, 205–225.
- Thompson, C.H. 1992 Genesis of podzols on coastal dunes in southern Queensland. I. Field relationships and profile morphology. *Aust. J. Soil Res.* **30**, 593–613.
- Torreano, S. 2004 Forests and soil development. *Encyclop. For. Sci.* **3**, 1208–1216.
- Valentine, H.T. 1997 Height growth, site index, and carbon metabolism. *Silva Fenn.* **31**(3), 251–263.
- Vanclay, J.K. 1994 *Modelling Forest Growth and Yield*. CAB International, Wallingford. XVII + 312 pp.
- Vanclay, J.K., Skovsgaard, J.P. and Hansen, C.P. 1995 Assessing the quality of permanent sample plot databases for growth modelling in forest plantations. *For. Ecol. Manage.* **71**, 177–186.
- Wakeley, P.C. 1954. The growth intercept method of site classification. In *Proc. 3rd Ann. For. Symp. Louisiana State Univ., Baton Rouge*, pp. 32–33.
- Walker, J., Thompson, C.H., Fergus, I.F. and Tunstall, B.R. 1981 Plant succession and soil development in coastal dunes of eastern Australia. In *Forest Succession: Concepts and Application*. West, D.C., Shugart, H.H. and Botkin, D.B. (eds). Springer, NY, pp. 107–131.
- Walker, J., Thompson, C.H., Reddell, P. and Rapport, D.J. 2001 The importance of landscape age in influencing landscape health. *Ecosyst. Health* **7**, 7–14.
- Weiler, M. and McDonnell, J.J. 2004 Water storage and movement. *Encyclop. For. Sci.* **3**, 1253–1260.
- Weise, W. 1880 *Ertragstafeln für die Kiefer*. Verlag von Julius Springer, Berlin. VI + 156 pp. + 7 lithographierten Tafeln.
- Weiskittel, A.R., Hann, D.W., Kershaw, J.A. and Vanclay, J.K. 2011 *Forest Growth and Yield Modelling*. Wiley-Blackwell. XIII + 415 pp.
- West, P.W. 2004 *Tree and Forest Measurement*. Springer, Berlin, Heidelberg. XII + 167 pp.
- Wiedemann, E. 1932 *Die Rotbuche 1931*. M. & H. Schaper, Hannover. 191 pp.
- Wiedemann, E. 1937 *Die Fichte 1936*. M. & H. Schaper, Hannover. 248 pp.
- Willoughby, I., Stokes, V. and Kerr, G. 2009 Side shelter on lowland sites can benefit early growth of ash (*Fraxinus excelsior* L.) and sycamore (*Acer pseudoplatanus* L.). *Forestry* **82**, 199–210.