Forest site productivity: a review of the evolution of dendrometric concepts for even-aged stands

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Summary

Forest site productivity is the production that can be realized at a certain site with a given genotype and a specified management regime. Site productivity depends both on natural factors inherent to the site and on management-related factors. This review of the evolution of site assessment highlights three tenets of forest site productivity: the height–age site index, Eichhorn's rule and the thinning response hypothesis. These tenets rely on the hypotheses that height growth correlates well with stand volume growth, that total volume production of a given tree species at a given stand height should be identical for all site classes and that stand volume growth is independent of thinning practice for a wide range of thinning grades. The maturation of long-term field experiments has provided for the revision of these hypotheses, and contributed to an understanding of situations where they do not hold. This led to the introduction of the concept of yield level, the stand volume growth per unit of height growth. The use of the yield level theory for estimating site productivity has facilitated the development of a three-dimensional model of the relationship between stem number, quadratic mean diameter and stand basal area. Given this model, 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.

Introduction

Planning and implementing sustainable management of forests require that a range of ecological, economic and social conditions are evaluated and considered carefully. As part of this process, forest managers and planners summarize information on the present and predicted future condition of a forest using various indicators selected for their usefulness in evaluating consequences of different management actions. In many situations, reliable estimates of wood production are essential for sustainable forest management. Such estimates depend on silvicultural practices, on estimates of site productivity and on growth models or yield tables.

In this paper, we examine the estimation and reliability of forest site productivity indicators for even-aged forests, based on mensurational or dendrometric characteristics of the trees. Throughout, we concentrate on concepts and principles rather than underlying processes, sampling practices

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and mensurational procedures. We briefly introduce the concept of forest site productivity and its evolution. In the appendix, we provide brief biographies of the individuals (marked with an asterisk at relevant places in the text) who were first to identify key principles or were influential in shaping the twentieth-century paradigm of forest productivity.

The concepts of site, site quality and forest site productivity

The term *site* refers to a geographic location that is considered homogeneous in terms of its physical and biological environment. In forestry, site is usually defined by the location's potential to sustain tree growth, often with a view to site-specific silviculture. Sites may be classified into *site types* according to their similarity regarding climate, topography, soils and vegetation. Site classification may serve a range of management purposes, including ecological stratification for optimizing the estimation of forest site productivity.

Although the terms site quality and site productivity are often used interchangeably, they are not synonymous. *Site quality* refers to the combination of physical and biological factors characterizing a particular geographic location or site, and may involve a descriptive classification. The properties that determine site quality are generally inherent to the site, but may be influenced by management.

Site productivity is a quantitative estimate of the potential of a site to produce plant biomass, and embraces two concepts: the site potential and that part of the site potential realized by a given forest stand (Figure 1). In a broad sense, the *site potential* is the capability of the site to produce plant biomass (cf. net primary production), irrespective of how much of this potential is utilized by the vegetation. The term site productivity is often used in a more narrow sense to refer to that part of the site potential that is or is expected to be realized by the trees for wood production.

In that sense, forest site productivity may be defined as the potential of a particular forest stand to produce aboveground wood volume, referring to the production unit formed by the site and the stand of trees in concert. Generally, aboveground volume production is calculated on stem wood volume for conifers, but may include branch volume for broadleaved tree species. For many purposes, the maximum mean annual volume increment is considered a suitable measure of site productivity.

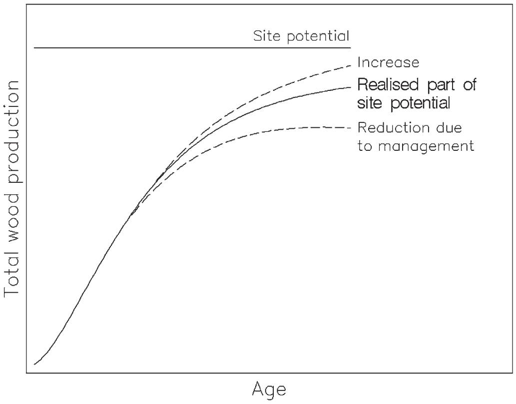

Figure 1. The concept of forest site productivity in terms of current annual volume increment *vs* age. The full site potential for wood production (horizontal line) is only briefly realized by a given forest stand (bold line). Management practices may increase or decrease stand productivity (dashed lines) at any stage of stand development and these changes may be permanent or transient. For simplicity, the site potential is considered constant.

Within this narrower context, site productivity is often quantified as an index, typically site class or site index. Such indices are defined in different ways and are widely used for management purposes. Most commonly, site indices are based on or derived from estimates of stand height at a given age. Site productivity indicators also reflect site quality because productivity, or the realizable part of the site potential for volume growth, is related to the site quality.

We use the term site productivity in the narrow sense, namely the production that can be realized at a certain site with a given genotype and a specified management regime. This depends on both natural factors inherent to the site and on management-related factors. In managed forests, the inherent site potential is determined largely by soil characteristics and climatic factors. Management can affect the production potential through silvicultural options such as site preparation, choice of tree species, provenance, spacing, thinning and regeneration method. Additionally, environmental conditions in the surrounding forest (e.g. wind-sheltering effect of neighbouring stands) and practical aspects of forest operations (e.g. damage to crop trees and soil compaction) may also influence the production potential. In turn, management may also affect site quality and thus the inherent site potential.

Approaches to assessing site productivity

Forest site productivity may be assessed in several ways, usually classified as either *geocentric* (earth-based) or *phytocentric* (plant-based) methods (e.g. Hägglund, 1981; Leary, 1985, pp. 45–56; Wenk *et al*., 1990, pp. 235–258; Vanclay, 1994, pp. 134–155). Geocentric productivity indicators are based on site properties, including physical characteristics of climate, topography or soil. Phytocentric indicators are based on characteristics of the vegetation. In forestry, the phytocentric indicators often relate to the forest stand, the trees comprising the stand or components of the individual trees, and can be classified as *dentrocentric* or *dendrometric*. Either category may be considered direct or indirect, to a greater or lesser extent, depending on how closely the indicator is related to production of wood volume (Table 1).

This classification into dendro-, phyto- or geocentric is usually straightforward, whereas the distinction of direct or indirect is a relative one that may depend on scale and other factors. Some indicators, however, are not strictly phyto- or geocentric, including those based on root depth and humus form.

This classification does not presuppose that one approach is ‘better’ or preferable to another. Rather, we suggest that the most suitable method may depend on the purpose and scale. For example, for a given species within a growth region, stand height might be the most practical productivity indicator because it is well correlated with volume growth, whereas a combination of climatic variables might yield only a rough estimate of productivity. However, climatic indicators such as the Paterson index based on temperature, precipitation and radiation (Paterson, 1956, 1962) may be more appropriate for general comparisons across species and regions.

Because of its close relationship to site properties and thus to site potential, the geocentric approach has been widely used in agriculture for site assessment, for example, by using the textural classification of the upper soil strata as a basis for site index estimates. In forestry, however, the geocentric approach may not always be practical, affordable or sufficiently accurate for management applications. A similar argument holds for classifications based on ground vegetation. Thus, the dendrocentric approach dominates, and usually one or a combination of several easily measured tree or stand variables are used to indicate site productivity in practice.

Table 1: Classification of some methods for assessing forest site productivity

			Phyto-centric	
View	Geo-centric	Intermediate		Dendrocentric
Direct	Soil texture Soil moisture and nutrient analysis Photosynthetically active radiation			Volume measurement
Intermediate	Soil parent material	Rooting depth Humus form	Ground vegetation	
Indirect	Climate Physiography Geographical coordinates		Plant community characteristics	Site index by stand height

The classification and relative position of each method (geocentric–phytocentric and direct–indirect) may vary depending on circumstances.

Here, we focus mainly on this approach to site assessment.

Evolution of forest site productivity estimation

Several indicators have been tested and are being used for different forest types, but stand height seems to be the most widely used, accepted and versatile site productivity indicator for even-aged forests (Hägglund, 1981; Kramer, 1988; Wenk *et al.*, 1990; Vanclay, 1994; Pretzsch, 2001, 2002; Avery and Burkhart, 2002; Burger, 2004; Skovsgaard, 2004). In this section, we briefly outline the historical background and point out some crucial research results that helped shape and continue to influence our comprehension of forest site productivity.

Site classification by stand height: the first fundamental

With the introduction of scientific methods in forestry in Europe 200–300 years ago, the first attempts to assess and classify the production potential of forest sites took a geocentric approach. Initially, it was common to use broad classifications, such as 'low-altitude clay-loam soil of medium production capacity for beech' (e.g. Hartig, 1795, 1847; Paulsen 1795; Reventlow, 1816, 1879). Later, site classes were indexed by standing volume (e.g. von Wimpfen, 1836; Pressler, 1870). Wood production was estimated using site-specific 'experience tables', the precursors for yield tables and growth models. Experience tables were constructed on the basis of an assumed average or index stand, i.e. an individual stand that was supposed to reflect typical stand development.

Towards the end of the nineteenth century, it was realized that the stand mean height at a given age is a practical measure of site productivity, and a classification based on species and typical site-specific height development patterns was introduced (Figure 2). As a measure of site productivity, *site class* is often denoted by a class variable, whereas *site index* usually refers to the expected (or realized) stand height at a given reference age. For example, site classes 1, 2, 3 and 4 for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Denmark (Henriksen, 1958) refer to site indices or stand heights 28, 24, 20 and 16 m, respectively, at the age of 50 years from seed.

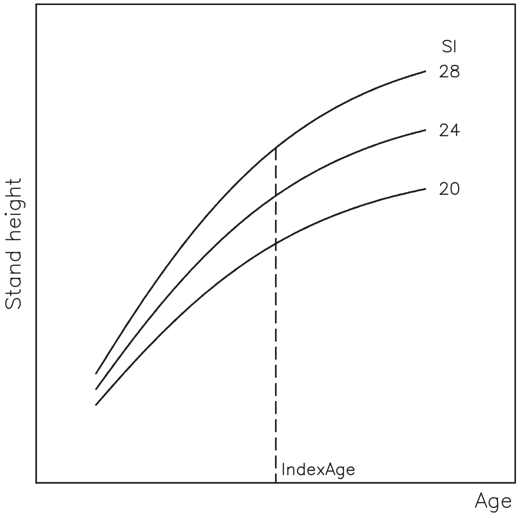

Figure 2. The site index hypothesis. According to the site index hypothesis, the productivity of forest sites can be classified by stand height at a given age. In this example, the three site index curves correspond to stand heights 28, 24 and 20, respectively, at the index age.

The introduction of site classification by stand height was a consequence of some 100 years of work with experience tables that lacked an unambiguous indicator of the current or future stand volume growth. Although Oettelt (1764, p. 32–33) hinted at stand height as a productivity indicator, Heyer* (1841, p. 23) was probably the first to identify, on a scientific basis, a correlation between height growth and volume growth. Subsequently, several German researchers suggested height as an indicator of site productivity, but the honour is usually attributed to Baur* (1877), who was the first to construct a yield table with site classification by stand height.

The original argument for choosing height as an index of site productivity was that the relation between mean height and age resembled the relation between crop volume and age (Baur, 1877, 1881; Gyldenfeldt, 1883, p. 39). The validity of this argument is due to the fact that, at that time, forest stands in this part of the world were thinned lightly, often removing only dead and suppressed trees. Nonetheless, the key argument is that stand height or height growth should be well correlated with stand volume growth.

In a broader perspective, the use of stand height as an indicator of site productivity generally relies on the belief that in even-aged stands the height growth of the largest trees is roughly independent of the stem number. This holds for a wide range of initial spacings and thinning grades commonly used for many species in forestry practice, provided that thinning is not from above (e.g. Sjolte-Jørgensen, 1967; Evert, 1971; Bredenkamp, 1984; Lanner, 1985). However, it is well-established that high as well as low stem densities, due to spacing or thinning, may influence stand height compared with similar stands at more ‘normal’ stem densities (e.g. Bryndum, 1980; Harrington and Reukema, 1983; Johannsen, 1999; MacFarlane *et al.*, 2000; DeBell and Harrington, 2002; Kerr, 2003). This seems to depend on several factors, including site conditions, age and shade tolerance of the species.

Trees used in the estimation of site index should rank among the upper social classes. Top and dominant height, which represent these, are least affected by thinning and are the most stable height-based indicators of site productivity.

Classification of site productivity by stand height soon became firmly established as part of the German norm for yield tables (see Ganghofer, 1881, pp. 361–362). Despite some initial scepticism (e.g. Weise, 1880; Oppermann, 1887, pp. 208–209; Hartig, 1892, p. 173), height was soon generally accepted as the most expedient indicator of site (e.g. Gram, 1879, pp. 214–215; Jonson, 1914). A few years later, a similar debate in North America (referenced by Tesch, 1981; and Monserud, 1984a, 1987) also led to stand height as the established indicator of forest site productivity (see Society of American Foresters, 1923). Similar debates have occurred elsewhere.

Periodic height growth has been used as an alternative site productivity indicator. It appears to have been developed independently by several researchers (e.g. Bull, 1931; Møller, 1933; Ferree *et al.*, 1958; Wakely and Marrero, 1958), and has become known as the height growth intercept method.

Periodic height growth may be more reliable than stand height in young stands, in stands of unknown age, in stands where the current potential for volume growth is not well reflected in stand height (e.g. where height growth has been hampered by frost or browsing) and where the site-specific growth pattern deviates from that implied in the classification system. When damage due to frost or browsing in youth is a problem, site index estimation is often based on age and height above a certain level (typically 1.30 m). Site productivity estimates derived from short-term observations of periodic height growth are liable to climatic and other variations in growth and may be less accurate than estimates based on stand height.

Over time, several methods have been used to establish site-specific height growth patterns (e.g. Hägglund, 1981; Tesch, 1981; Clutter *et al.*, 1983; Holten-Andersen, 1989; Pretzsch, 2001, 2002; Avery and Burkhart, 2002). Early site class and site index curves were established using hand-drawn lines and simple mathematical procedures, but now statistically based methods prevail. These may employ a range of different approaches using either individual tree or stand data, temporary or permanent plot data, total height or periodic height growth as well as the average of all observations, the average of selected observations or the observation extremes to establish typical height–age development. The underlying model may allow for anamorphic or polymorphic development (i.e. fixed or flexible proportions between site classes; Bailey and Clutter, 1974) and may or may not account for spatial and temporal correlations in data.

Site index curves may be indexed by stand height at a fixed age (the traditional approach) or one (or more) of the function parameters may be used directly as an indicator of site productivity. Each unique combination of these approaches has different implications for the resulting system.

Site classification by stand height has become one of the most universal practices in forestry, and is recognized as one of the most suitable indicators of site productivity for management purposes in even-aged forest stands (e.g. Hägglund and Lundmark, 1977, 1987a, b; Monserud, 1984b; Schönau, 1987; Rayner and Turner, 1990; Rayner, 1992).

Because forestry is concerned with the wood volume that can be realized, the maximum mean annual volume increment is often considered a more useful measure of site productivity than an index based on stand height or height growth. An index that represents volume production (i.e. m^3 ha^{-1} y^{-1}) allows for more direct and meaningful comparisons across species, site types and growth regions than an index based on stand height at a certain age. However, it is common for indices based on maximum mean annual volume increment to be derived from a correlation with stand height (e.g. Hamilton and Christie, 1971). The reliability of this alternative index may thus rely on both the correlation with stand height and the reliability of the original variable.

The widespread use of height or height growth as a site productivity indicator (or as the basis for one) relates to the fact that, in many situations, stand height or current height growth seems to correlate well with stand volume growth. In addition, height is a simple variable that is easy and inexpensive to measure and is generally not much affected by management practices. Site classification by stand height has its origins in plantation-like regular forests with good management records and in even-aged, single species, well-stocked stands of known age. However, it is also used for more complex or irregular forest types, with or without past management history or records (Vanclay and Henry, 1988; Vanclay, 1992).

From being an interim measure of site productivity, site classification by height has gained broad acceptance to the extent that site class or site index is often assumed to be the 'true' current or potential volume production, rather than simply an indicator that may or may not reflect the site potential. Rightly or wrongly, the site index hypothesis (i.e. site classification by height) has become part of the prevailing paradigm as a fundamental principle, an unquestionable cornerstone in our comprehension of forest growth.

Eichhorn's rule: the second fundamental

A further consequence of the early efforts to construct yield tables is the so-called Eichhorn's rule. According to Eichhorn's rule, the total volume production of a given tree species at a given stand height should be identical for all site classes (Figure 3). Eichhorn* (1902, p. 59) originally discovered that the volume of crop trees in lightly thinned stands of European silver fir (*Abies alba* Mill.) is a function only of stand height (e.g. irrespective of age and basal area). Subsequently, this was confirmed for other tree species (Eichhorn, 1904; Gehrhardt, 1909), and the relationship was extended by Gehrhardt* (1921) to apply to total volume production or gross volume yield. The concept has also been used in other fields, for example, to define regional patterns of vegetation production (e.g. Specht and Specht, 1999).

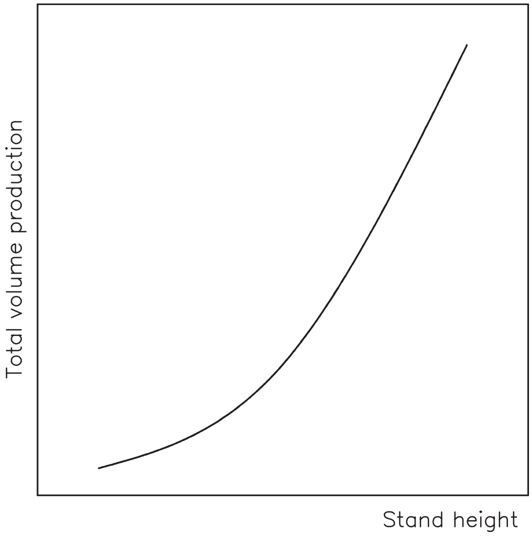

Figure 3. Eichhorn's rule. Eichhorn's rule assumes that the total (accumulated) production of aboveground wood volume at a given stand height is independent of age and site for a given tree species.

The extended Eichhorn's rule has been widely used in the construction of yield tables and growth models (e.g. Mitchell, 1969, 1975; Alder, 1980; Edwards and Christie, 1981; Holten-Andersen, 1989; Philip, 1994; Peterson *et al.*, 1997; Savill *et al.*, 1997). It can also be very useful when adjusting general models to deviating local growth or management conditions. The extended rule postulates that any two stands with identical height growth and identical initial height will have identical volume growth, irrespective of any differences in age. This implies that stand volume growth can be estimated from height growth, given the availability of a general model or a reference stand of the same species with known volume growth. Eichhorn's rule is often used without regard for possible differences between stands in initial spacing, thinning regime or provenance.

The thinning response hypothesis: the third fundamental

From the late nineteenth century, thinning experiments were installed in Europe, and subsequently in other parts of the world, to help optimize stand treatments in managed forests. One of the objectives was, and still is, to research effects of different thinning treatments (thinning grade, intensity, frequency, timing and type). A major result from these and other thinning experiments is the notion that thinning does not influence stand volume growth significantly for a wide range of thinning grades or stocking densities, whereas heavier thinning beyond this range reduces volume growth (Figure 4). We refer to this as *the thinning response hypothesis*.

The empirical evidence for the thinning response hypothesis stems mainly from stands thinned predominantly from below. Unless stated otherwise, the hypothesis generally refers to total aboveground stem volume for conifers and total aboveground wood volume for broadleaves.

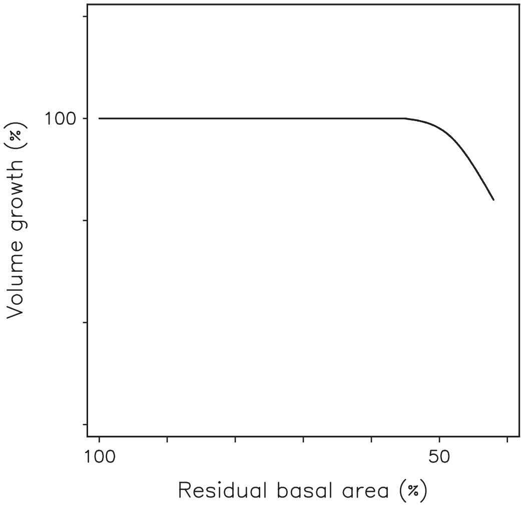

Figure 4. The thinning response hypothesis. For many tree species, stand volume growth is thought to be independent of thinning practice for a range of thinning grades stretching from the unthinned stand, down to a residual basal area of ~50 per cent of maximum basal area. The accumulation of maximum basal area occurs in unthinned stands only.

Several scientists contributed to the formulation of the thinning response hypothesis in the gradual process of interpreting experimental results for different site types, tree species and stand ages. The hypothesis was promoted and quantified most notably by Wiedemann* (1932, pp. 49–56; 1937, p. 156; 1951), Langsæter* (1941, pp. 173–194) and Møller* (1944, pp. 133–139; 1951; 1954), although in slightly different forms.

The main differences relate to the nature of their data, to the choice of reference for comparing different thinning treatments across species, sites and ages and to details in the interpretation of the thinning response. Wiedemann studied thinning from below and crown thinning. He used plots thinned moderately from below as reference. Langsæter specifically considered the response of open-grown forest and very dense stands. He used the unstocked site as a logical reference (i.e. no trees = no growth). Møller favoured the fully stocked unthinned stand as a reference. Both Wiedemann and Møller maintained the view that thinning generally does not influence stand volume growth significantly for a wide range of thinning practices (from none to heavy thinning), whereas Langsæter was more concerned with the pattern of the response.

The thinning response hypothesis has had a major influence on thinning practices for even-aged forest types in many parts of the world (e.g. Baur, 1964; Daniel *et al*., 1979; Shepherd, 1986; Smith, 1986; Henriksen, 1988; Evans, 1992; Lewis and Ferguson, 1993; Florence, 1996; Savill *et al*., 1997; Nyland, 2002). It is based on the notion that the production efficiency is greatest at the lowest stocking density that achieves full use of the site potential for timber production. However, in practice, other factors (such as timber quality, price assumptions, harvesting costs, risk of windthrow and regeneration options) also need to be considered at any time during the rotation when determining desired stocking density.

For given site conditions and a given spacing or initial stem number at stand establishment, the unthinned stand or control plot will support the highest possible basal area (or stand volume) of live trees at any stage of stand development. All other things being equal, the thinning grade of any stand or plot may thus be gauged on a relative scale by its residual basal area relative to the basal area of an unthinned stand or plot. Similarly, stand volume growth may be scaled relative to that of an unthinned stand or plot.

For many tree species, stand volume growth is thought to be independent of thinning practice for a range of thinning grades stretching from the unthinned stand, down to a crop volume or basal area of ~50 per cent of maximum crop volume or basal area (as shown in Figure 4). This is most notably the case for shade-tolerant species. This assumption of a 50 per cent threshold is often used as a rule of thumb in the absence of more specific information.

A principle similar to that of the thinning response hypothesis also holds for spacing or stem number at stand establishment (e.g. Sjolte-Jørgensen, 1967; Reukema, 1979; Oliver and Larson, 1990; Smith and Strub, 1991). However, increased spacing may lead to reductions in early stand volume growth that are not fully regained later (e.g. Sjolte-Jørgensen, 1967; Hamilton and Christie, 1974; Adlard, 1980; Kilpatrick *et al*., 1981; Henriksen, 1988).

Obviously, the use of stand height as an indicator of site productivity and thus of past, current and future volume growth is closely related to the thinning response hypothesis. If thinning (or spacing) leads to changes in height or stand volume growth compared with the reference situation (i.e. the site index curve), the reliability of growth predictions may deteriorate and their use may be limited to certain management regimes. Similar arguments hold for Eichhorn's rule.

Assmann's theories: questioning the three fundamentals

In the 1950s, Assmann* analysed a number of experiments and yield tables. His analyses challenged the general validity of the three fundamental principles of forest growth, namely height as an indicator of site productivity, Eichhorn's rule and the thinning response hypothesis.

With the increasing number of experiments, growth models and yield tables, large-scale geographic gradients in stand volume growth for identical site index had become apparent, for some of the main species in Europe. Some found that increasing precipitation and temperature could lead to higher volume growth rates without commensurate increases in height growth. In a study of these discrepancies, Assmann (1955, 1959) demonstrated that even within the same growth region the correlation between site index and volume production is not always straightforward (summarized by Assmann, 1961, pp. 154–182; 1970, pp. 158–186; Kramer, 1988, pp. 49, 94–95, 118–125; Wenk *et al*., 1990, pp. 245–253; Pretzsch, 2001, pp. 89–93; 2002, pp. 309–310).

For a given, well-defined silviculture (site preparation, initial spacing, thinning regime, etc.,) considerable site-dependent variations may occur in total volume production at a given height. Subsequently, this has been demonstrated for a number of tree species, thinning regimes (including unthinned stands), site types and growth regions (e.g. Henriksen, 1958; Kennel, 1973; Schmidt, 1973; Hasenauer *et al*., 1994; Vanclay *et al*., 1995; Skovsgaard, 1997). For identical species, height and thinning regime, variations may be as large as ±30 per cent from the average.

Weise* (1880), one of the early sceptics of height-based site classification, was also aware of such site-dependent variations and therefore divided each height site class into sub-classes according to specific levels of volume production. Subsequently, Gehrhardt and Wiedemann used similar approaches in some of their yield tables.

In Central Europe, the total volume production at a given stand height is often referred to as the *yield level*. It is also known as the production class or the increment level. Stands of different yield levels have different trajectories for height–total volume production (Figure 5). The yield level is thus another measure of site productivity in terms of volume production per unit of height growth. A distinction is made between the general and the specific yield level. The *general yield level* is considered without reference to age. The *specific yield level* refers to a given age, and thus to a given height site index.

Differences in yield level may be due to climate, soil, provenance, establishment method, stand treatment or other factors. In terms of aboveground mensurational characteristics, variations in yield level are primarily due to variations in basal area production, whereas differences in form factor have no or very little influence. The

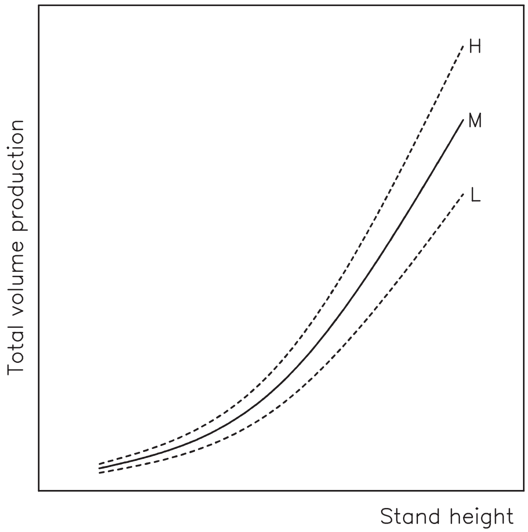

Figure 5. Assmann's yield level theory. The total volume production at a given stand height is referred to as the yield level. It is also known as the production class or the increment level. Stands of different yield levels have different trajectories for height–total volume production. In this example, the yield levels H (high), M (medium) and L (low) are identified. Note that stands do not necessarily progress along these curves at identical rate or at a rate which correlates with yield level.

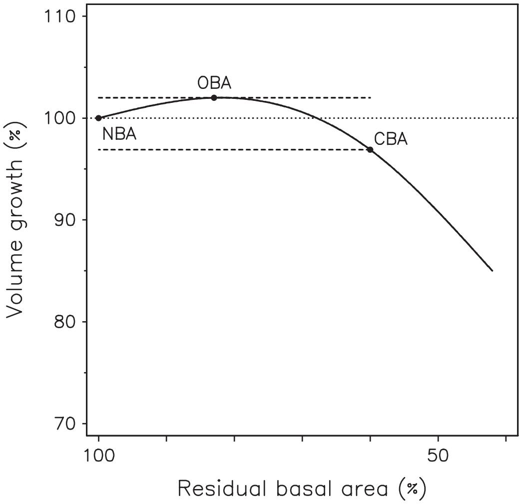

Figure 6. Assmanns theory of natural, optimal and critical basal area. For given site conditions and a given spacing or initial stem number at stand establishment, the unthinned stand or control plot will support the highest possible basal area of live trees at any stage of stand development. This is referred to as the natural basal area (NBA). The basal area at which the largest stand volume growth is achieved during the period concerned is referred to as the optimum basal area (OBA). The basal area at which volume growth is 5 per cent less than at the optimum is referred to as the critical basal area (CBA). In this example, optimum basal area is located at 83 per cent of the natural basal area. Here, volume growth is at 102 per cent. A 5 per cent reduction in volume growth, compared with that at the optimum, appears at a basal area of 60 per cent. Here, volume growth is at 96.9 per cent, compared with the unthinned stand.

yield level may be defined in a qualitative (e.g. high, medium, low) or quantitative way (e.g. 475 m^3 ha^{-1} at top height 20 m).

Assmann (1950, 1954, 1956) also clarified concepts and details regarding the effects of thinning on stand volume growth. Using unthinned control plots as a reference, he demonstrated that volume growth may be more sensitive to thinning than indicated by the thinning response hypothesis. The specific response (both nature and relative amount) may depend on tree species, age and site (summarized by Assmann, 1961, pp. 222–230; 1970, pp. 227–235; Kramer, 1988, pp. 85–87; Pretzsch, 2001, pp. 44–47; see also Henriksen, 1952; Holmsgaard, 1956).

Assmann (1950, 1954, 1956) offered a reference frame for analysing thinning effects, by suggesting the unthinned control as the standard, with mean basal area between consecutive thinnings as the indicator of thinning grade (Figure 6). For long-term comparisons, mean basal area for each thinning interval should be weighted according to the interval length. To facilitate comparisons across species, sites and ages, the thinning grade and stand volume growth of the unthinned reference is set to 1 (or 100 per cent) and the thinning grade and volume growth of all other plots measured on a scale relative to this standard.

Based on eco-physiological and statistical considerations, Assmann further suggested three characteristic basal area values to summarize thinning response patterns. For given site conditions and a given spacing or initial stem number at stand establishment, the unthinned stand or control plot will support the highest possible basal area at any stage of stand development. This *maximum basal area* of live trees is referred to as the *natural basal area*. The basal area at which the largest stand volume growth is achieved during the period concerned is referred to as the *optimum basal area*. The basal area at which volume growth is 5 per cent less than at the optimum is referred to as the *critical basal area*. The definition of critical basal area is based on the assumption that 5 per cent is the statistically detectable deviation or change considering the expected mean error for volume growth estimates.

Depending on research objective, numerous approaches are possible within this frame for analysing thinning effects. For example, volume may refer to merchantable volume, optimum and critical basal area may be identified based on the economic return of different thinning treatments, the location of critical basal area may be set at some other, relevant level of basal area or volume may be replaced by dry matter production.

Studies have shown that unthinned stands with an initial stem number above a certain limit converge towards a site-specific natural basal area (e.g. Pienaar and Turnbull, 1973). Specifics of the thinning response pattern may vary with species and site as well as with thinning type, timing and frequency (e.g. Bradley, 1963; Bryndum, 1969a, b, 1978, 1987; Butcher and Havel, 1976; Hamilton, 1981; Harrington and Reukema, 1983; Horne *et al*., 1986; Kramer, 1988; Wenk *et al*., 1990; Eriksson *et al*., 1994; Kerr, 1996; Skovsgaard, 1997; Varmola *et al*., 2004; Slodicak *et al*., 2005).

With shade-tolerant tree species, stand volume growth is often quite insensitive to thinning over a broad range of thinning grades (when thinning from below), whereas thinning of light-demanding species often leads to a loss of volume production. Sensitivity to thinning usually increases with increasing age, leading to increased reductions in volume growth after thinning, with reductions occurring at lighter thinning regimes than at earlier ages. However, moisture stress (drought or waterlogging) may confound these thinning responses. This emphasizes the relevance of establishing site- and species-specific response patterns to thinning and the need to consider these in forest management.

In summary, the results regarding possible site-dependent variations in volume production for identical stand height contradict the site index hypothesis and Eichhorn's rule. The results regarding possible variations in the effects of thinning on stand volume growth specifically falsify the 50 per cent interval of the thinning response hypothesis (and other invariant intervals) and, in turn, Eichhorn's rule.

However, the revised hypotheses, commonly known as Assmann's yield level theory and Assmann's theory of natural, optimal and critical basal area (Assmann, 1961, 1970), have had relatively little impact on foresters' conception of forest site productivity and their use of productivity indicators. For example, unlike the three fundamental principles, the yield level theory is rarely mentioned in textbooks, scientific reviews or other reference works outside Central Europe. The effect of thinning on stand volume growth remains an important research topic and a key issue in textbooks, but analyses often lack a rigorous frame of reference for the evaluation.

Approaching a simple, three-dimensional indicator of site productivity

The lack of a simple correlation between site index and yield level causes difficulties in accurately assessing site productivity. Some indicators of yield level have been suggested (e.g. Assmann and Franz, 1965; Franz, 1965, 1967; Kennel, 1973; Carbonnier, 1975; Bergel, 1985, 1986), but most are site specific. The underlying model for quantitative yield level indicators is often overly complicated or difficult to use in practice. Thus, yield level is generally accommodated in a qualitative way, relying on a classification into growth regions or site types.

In terms of common mensurational characteristics, variations in yield level are mainly due to variations in basal area production at breast height. However, thinning in managed forests detracts from the utility of basal area as a site productivity indicator. As suggested by Assmann (1961, 1970), this emphasizes the need to install and maintain unthinned plots as a reference for thinning and other silvicultural decisions and as benchmarks for growth predictions. However, the practice of unthinned reference plots has not been widely adopted in forestry practice or in scientific experiments not requiring unthinned reference data for other purposes.

The yield level concept involves using the potentially realizable part of the site potential for volume production as a site productivity indicator, and then adjusting for management practices and other factors. Inspired by the earlier work of Reineke (1933) and others, Sterba* (1975, 1981, 1985, 1987) developed a simple *stand density index* (SDI) based on quadratic mean diameter and stem number that captures variations in basal area growth. Drawing on the work of Skovsgaard (1997), we explain the idea using simple graphics rather than offering the full derivation of formulas.

In the three-dimensional space of quadratic mean diameter (D_g), stem number (N) and stand height (H), any stand will develop along a trajectory in a site-specific plane $D_g = 1/(AN + B)$, where A and B are power functions of H (Figure 7). Squaring D_g to obtain a similar plane for stand basal area (G) yields $G = (\pi/4) \cdot N/(AN + B)^2$ (Figure 8). Solving for maximum basal area yields $G_{max} = \pi N/(16B)^2$, which is an indicator of the site potential for tree growth. This situation corresponds to the ridge that is defined in the G-plane by G_{max} for any given height (Figure 8). Unthinned stands that utilize the site potential as much as biologically possible should develop along this ridge. Others, and even unthinned stands, may develop along a different trajectory.

Solving for N at G_{max} yields $N_{Gmax} = C(D_g)^E$, where C and E are constants. The estimated N_{Gmax} at a stand diameter of $D_g = 25$ cm is used as an SDI for the G_{max} situation and is thus an index for that part of the variation in total volume growth that is not captured by the site index. The constants C and E relate arithmetically to parameters of the functions A and B. This allows for a direct estimation of E and SDI_{max} with the original $D_g = 1/(AN + B)$ equation.

To ensure reliable determination of site-specific planes in the D_g–N–H space, a wide range of stand conditions should be sampled. Good estimates require a large variation in stem number. A sufficient range of diameter and height is normally provided by natural stand development. Stand data used to

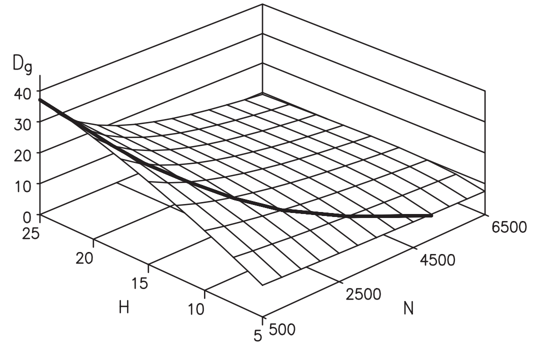

Figure 7. A three-dimensional space of quadratic mean diameter (D_g), stem number (N) and stand height (H). An unthinned stand will tend to develop along a trajectory in a site-specific plane, viz. $D_g = 1/(AN + B)$, where A and B are power functions of H. The line in bold is a possible trajectory for a given stand from (H, N, D_g) = (5, 5000, 8.0) to (25, 500, 37.5). For this stand, the period from stand establishment until the onset of stem number reduction is not shown in the graph, but could for example be a constant stem number at 5000 per ha from a height of 0 to 5 m.

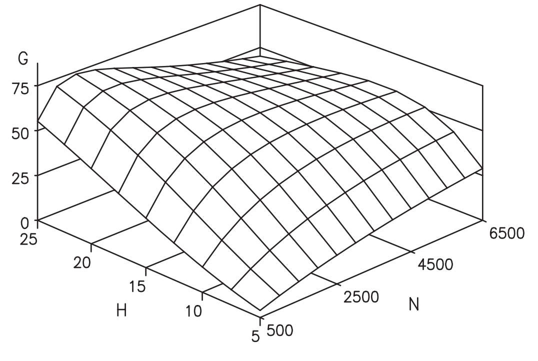

Figure 8. A corresponding plane for stand basal area (G), stem number (N) and stand height (H). Solving for maximum basal area yields G_{max} corresponding to the ridge that is defined in the G-plane by G_{max} for any given height. This corresponds to the site-specific maximum stand density. Unthinned stands that utilize the site potential as much as biologically possible should develop along this ridge. Others, and even unthinned stands, may develop along a different trajectory. Note that the ridge in this figure does not correspond to the stand development indicated with a bold line in Figure 7.

determine these planes need not reflect the G_{max} situation. This way the species-specific site potential for basal area growth may be estimated objectively without being observed directly.

Once the site-specific planes and the relation between SDI_{max} and the yield level (in terms of total basal area or total volume production) have been established, the SDI for any stand may be calculated as $SDI = N(D_g/25)^{-E}$, where E is a constant specific to species and growth region. When projected onto the two-dimensional D_g–N space (Figure 9), the G_{max}-reference trajectory for each site-specific D_g–N–H plane reflects the combination of stand diameter and stem number, which define yield level-specific SDIs.

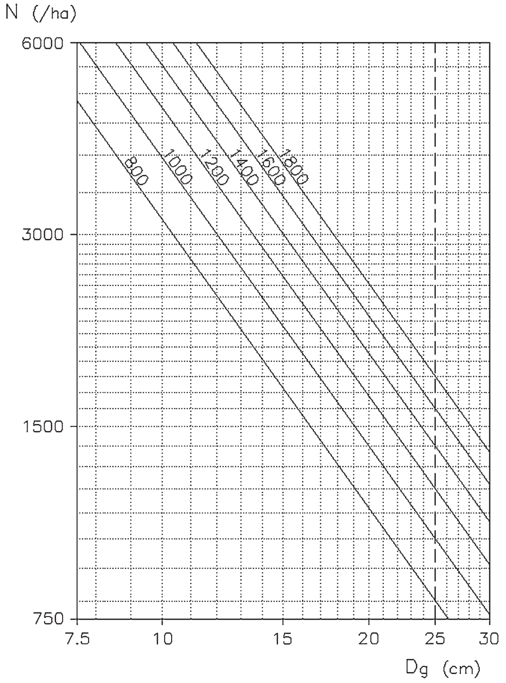

Figure 9. Maximum stand density projected onto the two-dimensional D_g–N space. The G_{max}-reference trajectory (Figures 7 and 8) for each site-specific D_g–N–H plane reflects the combination of stand diameter (D_g) and stem number (N), which define yield level-specific SDIs ($SDI = N(D_g/25)^{-E}$). In this example, the stand density lines range from an index value of 800 to 1800.

An immediate advantage of this SDI is that it reflects the visual impression of a forest stand. For example, with identical stand basal area, a low index value corresponds to a few thick trees, whereas a high index value corresponds to many thin trees. Visually, the stand with few thick trees will appear less dense than the stand with many thin trees, corresponding to their different index values.

This indicator of site productivity has been tested for different tree species and site types (e.g. Sterba, 1987; Hasenauer *et al.*, 1994; Skovsgaard, 1997), but its general utility remains unproven.

Quo vadis?

Site classification by stand height, Eichhorn's rule and the thinning response hypothesis have become deeply rooted concepts in forestry and in forest science. Yield tables and growth models in forest management and planning packages usually build on one or more of these concepts, and may not test the validity of these basic assumptions during model construction. General awareness of these concepts varies from country to country and from continent to continent, but they appear to be fundamentals of the dominant paradigm in forestry.

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). Despite documented examples where site potential and forest site productivity are not constant but change over time (e.g. Spiecker *et al.*, 1996; Valentine, 1997;), it is still widely held that site productivity should be constant and invariant within site types that are uniform with respect to climate, topography and soils. Users should be aware that this does not always apply.

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Conflict of Interest Statement

None declared.

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Appendix: Biographies

In this appendix, we provide brief biographies of foresters and scientists, who were first to identify key principles or were influential in shaping the twentieth-century paradigm of forest productivity. We attempt to identify the links that existed among these forest scientists, as we believe that these personal networks were instrumental in the evolution of concepts.

Heyer and his pupil Baur were influential in the development of site classification by stand height during the mid-1800s. The yield level theory was developed by Gehrhardt and his student Assmann, and the subsequent multi-dimensional interpretation was devised by Assmann's student Sterba. The origin of the yield level concept dates back to Weise, one of Baur's contemporaries and a sceptic of site classification by stand height. Although Weise and Gehrhardt worked at the same research institution, they were a decade apart, and we were unable to trace a personal connection.

In contrast, the idea of the thinning response hypothesis developed among a larger group of foresters over a wider geographical area. Several people contributed, and still contribute, to this process as field experiments for different tree species at different site types mature. Our interpretation is that Wiedemann, Langsæter and Møller formulated the foundation of the thinning response hypothesis, but were substantially influenced by colleagues locally as well as internationally.

Assmann, Ernst (Germany, 1903–1979)

Ernst Assmann studied forestry with Ernst Gehrhardt at the Forestry Academy of Hannover Münden in Braunschweig and subsequently worked briefly as an assistant to Gehrhardt. Later, Assmann worked in forestry practice from 1938 to 1951. During 1951–1972, he was professor of forest production at the University of Munich in Bavaria. In the 1950s, Assmann analysed a number of thinning experiments and yield tables. His analyses challenged the general validity of the three fundamental principles of forest growth, namely height as an indicator of site productivity (site index), Eichhorn's rule and the thinning response hypothesis. Assmann identified the need to supplement site index estimates by an indicator of the site-specific potential for volume growth, and he clarified important details of the thinning response hypothesis. In 1961, he published an authoritative textbook on the principles of forest growth (translated into English in 1970). Main biography source: Rubner (1994a) and Steinsiek (1996).

Baur, Franz Adolf Gregor von (Germany, 1830–1897)

Franz Baur studied forestry and forest science with Carl Heyer at the University of Giessen in Hessen. Subsequently, Baur was the first to publish a yield table with site classification by stand height. At that time (1877), Baur was head of the Forest Experiment Station in Württemberg. In 1868, Baur suggested the establishment of the German Federation of Forest Experiment Stations (established 1872), the precursor of IUFRO – International Union of Forest Research Organizations. In 1877, he was raised to peerage. During 1878–1897, Baur was the first professor of forest production at the University of Munich. In 1895–1896, he served as vice-chancellor of the university. Main biography source: Hradetzky (1980) and Rubner (1994b).

Eichhorn, Fritz (Germany, 1870–1939)

Fritz Eichhorn was a student at the Technical School of Karlsruhe in Baden during the period when Wilhelm Weise was one of the professors. In contrast to Weise's early findings, Eichhorn later identified the site- and age-invariant relationship between stand height and crop volume, which subsequently was extended to stand height and total volume production and became known as Eichhorn's rule. The initial discovery originated from his work with European silver fir at the Forest Experiment Station in Baden 1897–1900 and at the forestry department of the Technical School in Karlsruhe 1900–1902. Subsequently, Eichhorn worked in forest inventory, forestry practice and the central administration of forestry in Baden. He retired in 1928. Throughout his life, Eichhorn maintained an interest in scientific issues and remained a keen debater of forestry issues. Main biography source: Hasel (1980).

Gehrhardt, Ernst (Germany, 1867–1936)

Ernst Gehrhardt tested, further developed and promoted the use of Eichhorn's rule for a large number of tree species. At the same time, he also identified site-specific levels of volume production for a given stand height. Inspired by colleagues in Denmark, Gehrhardt was a leading figure in promoting early, heavy thinning, in stark contrast to forest management practices in Central Europe at that time. During 1923–1934, Gehrhardt was professor at the Forestry Academy of Hannover Münden in Braunschweig. Prior to this, he worked mainly in forest inventory and in forestry practice. Gehrhardt was a student at the University of Munich during the period when Franz Baur was one of the professors. Main biography source: Kropp and Rozsnyay (1998a).

Heyer, Carl Justus (Germany, 1797–1856)

Carl Justus Heyer was probably the first to identify the correlation between height growth and volume growth. His 1841 textbook is the earliest scientific source to mention the height–volume correlation. This subsequently led to the use of stand height as an indicator of forest site productivity. Heyer was educated in forestry by his father and worked in forestry practice as well as in science. During 1835–1856, he was professor of forestry at the University of Giessen in Hessen. Heyer was a keen proponent of statistically designed long-term field experiments as the basis of rational forest science. At a forestry meeting in 1845, Heyer suggested establishing a union of forest research institutions, but he did not live to see this vision fulfilled. Main biography source: Rozsnyay (1990).

Langsæter, Alf Erling (Norway, 1897–1986)

Alf Langsæter has become known internationally for his role with the thinning response hypothesis. In some parts of the world, the interval of thinning practices, for which stand volume growth remains unaffected by thinning, has become known as Langsaeter's plateau. Langsæter interpreted the thinning response in much the same way as Assmann subsequently did. During this period, Langsæter worked as a senior scientist with the Norwegian Forest Research

Institute in forest biometrics, inventory and growth modelling. Subsequently, he was professor of forest economics at the Norwegian Agricultural University 1946–1949. During 1949–1967, Langsæter served as director general of forestry in Norway. Main biography source: Samset (1986).

Møller, Carl Marenus (Denmark, 1891–1978)

Carl Mar: Møller took a leading role in the formulation of the thinning response hypothesis and strongly promoted 50 per cent as a rule of thumb for residual basal area. In some parts of the world, the interval of thinning practices, for which stand volume growth remains unaffected by thinning, has become known as Moller's plateau. Unlike Wiedemann and Langsæter, Møller communicated his ideas directly to a wider international audience. During 1927–1962, Møller was professor of silviculture at the Royal Veterinary and Agricultural University in Copenhagen. He published a textbook on forest mensuration (1951) and one on silviculture (1965). Main biography source: Nielsen (1982, 1986).

Sterba, Hubert (Austria, born 1945)

Hubert Sterba has been instrumental in the development of a three-dimensional indicator of forest site productivity by combining ideas and results from plant population biology and forest science. During 1973, he worked briefly with Ernst Assmann at the University of Munich in Bavaria. Since 1979, Sterba has been professor of forest production and biometry at the University of Natural Resources and Applied Life Sciences in Vienna. During 1986–1989, he served as vice-chancellor of the university. Main biography source: http://www.boku.ac.at/wafo/ma_hs_cur.htm accessed on 29 January 2006.

Weise, Paul Wilhelm Richard (Germany, 1846–1914)

Wilhelm Weise was one of the sceptics of height as an indicator of site productivity. However, he was also one of the first scientists to publish a yield table with site classification by stand height. Based on research plots covering most of Germany, Weise identified significant site-specific variation in volume growth for stands of identical site index as early as 1880. At that time, Weise worked with the Prussian Forest Experiment Stations in Eberswalde and Hannover Münden. Subsequently, he was professor at the Technical School of Karlsruhe in Baden 1983–1991 and director of the Forestry Academy in Hannover Münden 1891–1906. Main biography source: Kropp and Rozsnyay (1998b).

Wiedemann, Eilhard (Germany, 1891–1950)

Eilhard Wiedemann was instrumental in quantifying the thinning response hypothesis. This work was carried out mainly when he was professor at the Forestry Academy in Eberswalde 1927–1945. During 1927–1933, he also served as Head of the Prussian Forest Experiment Station in Eberswalde, and in 1933–1945 as its leader of forest production research. At the end of the Second World War, Wiedemann settled in the Federal Republic of Germany and became head of forest inventory in Lower Saxony and head of the newly established Lower Saxony Forest Research Institute. Wiedemann strongly opposed, on a scientific basis, contemporary ideas of continuous cover forestry. His influential textbook on the application of forest production principles in silviculture was published posthumously in 1951. Main biography source: Kropp and Rozsnyay (1998c) and Dittmar (2001).