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Assessing site productivity in tropical moist forests: a review

Jerome K. Vanclay

Faculty of Forestry, Royal Veterinary and Agricultural University, Thorvaldsensvej 57, DK 1871 Frederiksberg C, Denmark

ABSTRACT

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Reliable estimates of site productivity are essential for improved predictions of timber yields and for meaningful simulation studies. Few suitable techniques exist for tropical moist forests. Conventional indices such as site index cannot be estimated reliably for stands with many species or indeterminate ages. Emerging techniques require two steps: calibration and validation with permanent sample plots, and correlation with easily measured stand parameters. One promising index for the tropical moist forest is based on the expected diameter increment of individual trees adjusted for tree size and competition. Measures of stand height such as maximum stand height, canopy height and the height-diameter relationship may also prove useful. Proposed measures should satisfy four criteria: they should be reproducible and consistent over long periods of time; indicative of the site, and not unduly influenced by stand condition or management history; correlated with the site's productive potential; and at least as good as any other productivity measures available.

INTRODUCTION

It is obvious that some sites support luxuriant forest, whilst others are capable of supporting only 'poor' forests. This may be due to soil (fertility, drainage), climate (temperature and rainfall patterns), topography (altitude, aspect) and other factors, and may be reflected in the species present. Meaningful growth and yield forecasts require some evaluation of these site differences. Site-quality estimates may influence growth, mortality and recruitment predictions, and must be accurate, as any bias in evaluation of the site may introduce bias into all modelling results (Vanclay, 1988b).

The accuracy of any attempt to model forest systems depends largely upon the precision with which the site can be classified into homogeneous units (Gertner and Dzialowy, 1984; Smith and Burkhart, 1984). There are few techniques amenable to assessment of site productivity in tropical moist forests. Most texts ignore mixed forests; others suggest that "a stratification by forest type is usually the most efficient" (Carron, 1968, p. 134). However, some reliable techniques are emerging. This review gives an overview of many techniques, but focuses on those which can be used in operational timber inventory of forests with uneven or unknown ages. Such methods should provide an estimate of site productivity from data collected during a single visit to the site, without the need for laboratory analysis. Measures applicable only to even-aged stands (such as site index) are not considered, and readers are referred to Hagglund (1981) for such material. For a measure of site productivity to be useful, it must be (Vanclay and Henry, 1988): reproducible and consistent over long periods of time; indicative of the site, and not unduly influenced by stand condition or management history; correlated with the site's productive potential; and at least as good as any other productivity measures available.

TYPES OF SITE CLASSIFICATIONS

The following definitions based on Ford-Robertson (1971) are used in this paper: site index, the stand top (or predominant) height attained by a stand at a specified index age, often estimated for stands of other ages using a heightage curve; site quality, a descriptive measure of site determined by subjective methods, often by visual assessment into a relative (i.e. good-poor) classification; site class, a more objective classification into a number of classes; and site productivity, a general term for the potential of a certain species and site to produce timber. Site index, site quality and site class are approximate measures of the true site productivity.

Methods for assessing site productivity can be classified on the basis of methodology into predictive or descriptive, and qualitative or quantitative approaches. However, these distinctions are not clear-cut, as there is a range of methodology varying from one extreme to the other: descriptive systems, those which require several years of measurement, or measurements several years apart, in order to arrive at an estimate of site productivity; predictive systems, those which require measurement of some site or crop characters at a single point in time to predict the site productivity; qualitative systems, which result only in relative classes, and may be labelled numerically (Classes I, II, etc.) or otherwise (e.g. poor, good); and quantitative systems, which use a continuous variable, frequently height, as a measure of site, and the resulting measure of site may be expressed as a real number, or grouped into classes.

Qualitative classes require that borderline cases be resolved. Expansion of the system to recognize more classes (either to include new extremes or to encompass more classes) is difficult. Thus careful consideration must be given to the number of classes to be identified. Provided the difference in growth rate is significant, there is no advantage in having fewer classes than can be reliably recognized (Lewis et al., 1976). Quantitative systems are generally flexible and infinitely expandable, and eliminate the need to resolve borderline cases, but may give an inflated impression of precision. Predictive approaches require measurement of some characters of the site or stand at a single point in time. This measure may be transformed to derive an estimate of site productivity. Commonly such methods involve determining height at a known age, and transforming it to estimate site index or expected volume production. Site characteristics may also be used to estimate site productivity, and geographic regions, geology, vegetation types and crop appearance have also been used. For forest management and operational inventory purposes, predictive systems which enable site productivity to be estimated after a single visit are preferable to descriptive systems which require the maintenance and remeasurement of permanent plots. However, permanent plots are usually necessary to enable the development and validation of the more efficient predictive systems.

If a general growth or yield model is applied to data from a number of permanent sample plots with repeated measurements, the residuals will indicate the site productivity of the plots (Alder, 1980). Large positive residuals indicate a better-than-average site, small residuals indicate an average site, and negative residuals indicate a poorer-than-average site. Suitable residuals can be obtained simply by plotting basal area increment against stand basal area (e.g. Andel, 1975), or by regression analyses of individual tree increments with the plot as a qualitative variable (Vanclay, 1989b). In either case, measurements over a period of several years are required before site productivity can be estimated for use in the prediction of future yields from the site. If some correlation can be discovered between the residuals and some easily measured site or crop parameter, this system may be the first step towards a predictive system (Vanclay, 1989b). However, if no such correlation can be found, regional averages of these descriptive estimates of site productivity can be used as an interim measure.

Leary (1985) discussed a classification based on methodology (direct or indirect) and viewpoint (phytocentric or geocentric) (Table 1) . The phytocentric view assumes that total stand volume or phytomass production is the ultimate measure of a site’s productivity, while the geocentric view asserts the dependence of site productivity upon soil and climatic factors. Although direct methods are preferable, they are more difficult to quantify, and this has led to the proliferation of indirect methods. “The status of indirect phytocentric methods is so inflated that some speak of direct and indirect methods, not of site productivity estimation, but of site index estimation. This appears to be an unhealthy situation; what began as an interim solution (site index) to a difficult problem (geocentric approach) should not now be called the solution to the original problem” (Leary, 1985).

TABLE 1. A methodological classification (Leary, 1985)

View	Method	
	Direct	Indirect
Phytocentric	Volume of wood	Tree height
Geocentric	Soil moisture and nutrient status	Climate Land form
	Photosynthetically active radiation	Physiography Plant indicators

ASSESSING SITE FROM CROP PROPERTIES

Crop properties such as site index are widely used as measures of plantation site productivity, as they are usually easily measured and directly related to the utilizable production from the site. The most commonly used measure of site productivity is site index, but this requires an even-aged stand of uniform development. Various authors (e.g. Duerr and Gevorkiantz, 1938) have tried to apply similar techniques to mixed forests by identifying a main even-aged stand in the forest. Stage (1963) proposed a method which used height, age and the rate of early diameter growth to compensate for early suppression. Careful selection of subject trees may overcome some problems, but many difficulties remain (Monserud, 1988). However, all these techniques are of little use where age cannot be determined.

Stand appearance

The appearance of the stand, or stand type, may provide an indication of the site productivity. Lewis et al. (1976) reported that *Pinus radiata* plantations develop recognizable stand differences in general vigour and form, in crown density, in needle length and colour, in tightness and colour of bark, in green level and in degree of canopy formation at age of assessment, particularly prior to thinning. The South Australian site quality classes (seven classes) can be reliably recognized by experienced assessors from these qualitative characteristics. The method is relatively unaffected by the stocking variation normally experienced in South Australian plantations.

Vanclay (1989a) reported the use of visual assessment to classify tropical moist forest in north Queensland into two site quality classes (good, poor). Subjective assessments were generally reliable, and could be validated using a scoring procedure based on soil, species present, bole height and standing volume. Statistical analyses of stand basal area increment suggested that additional classes offered no advantage. This reflects on the ability to reliably classify sites, and not on the range of site productivity in the study.

Natural basal area

Pienaar and Turnbull (1973) observed that even-aged stands with initial stocking above a certain lower limit, converge towards an identical stand basal area, determined by the capacity of the site. If the premise that undisturbed sites tend towards equilibrium (Dawkins, 1958; Franz, 1967) is accepted, then the equilibrium or natural basal area may be assumed to be an expression of the site’s productivity (Assman, 1961; MacLean and Bolsinger, 1973b; Adlard, 1980). This assumption is implicit in many growth models (e.g. Botkin et al., 1972; Alder, 1977; Brandt et al., 1981). However, as stand basal areas may fluctuate over time (especially on small plots) even when undisturbed, the approach may be liable to error. In logged stands, remeasurements over long periods are needed to estimate the equilibrium basal area.

Havel (1980b) reported the use of natural basal area as an indicator of site productivity in Western Australia. In mixed stands, natural basal area may depend upon species composition. The natural basal area of any given site may be lower for light-demanding and crown-shy species than for shade-tolerant species. Thus natural basal area may depend on the successional status of the stand.

Stand height

The height attained by some species at the cessation of height growth is, in theory, a good indicator of site productivity (Westveld, 1933); but Smith (1984) questioned whether height growth ever ceases and supported his argument with data from 40 remeasured plots in temperate conifer stands up to 180 years of age. Stand height may be used as an estimator of site productivity if there are trees present in the stand which are sufficiently large to reflect the maximum height that the nominated species is likely to attain on that site. The concept is analogous to a site index with a very large index age.

Ogawa (1969) found potential maximum stand height a useful indicator of site productivity in tropical forests, and also found it to be highly correlated with total stand biomass. Havel (1975, 1980b) used stand height to estimate site productivity in jarrah (*Eucalyptus marginata*) forest in Western Australia. The average total height of dominant and co-dominant trees remaining after logging has been used as an indicator of site productivity of dipterocarp forests in the Philippines (Canonizado, 1978; Mendoza and Gumpal, 1987).

One difficulty in using stand height or total tree height is that the tree tops may be difficult to see in the tropical moist forest. In such cases, useful results may be obtained using height-to-crown break (H.C. Dawkins, personal communication, 1989) or merchantable height (Vanclay, 1989a). Other problems include the presence of emergent trees (e.g. *Araucaria),* the removal of large trees through logging and wind damage to tree tops. Where suitably large trees are not available, height-diameter curves can be used to estimate the asymptotic height. Ogawa (1969) predicted maximum stand height using the height-diameter equation

$$1/H_{max} = 1/H - b/DBH$$

where H_{max} is the maximum stand height, H and DBH are pairs of height and diameter measurements on individual trees, and b is a parameter to be estimated. This equation can be derived by fitting the equation $1/H = a - b/DBH$ to several pairs of height and diameter measurements from individual trees, and estimating the maximum stand height as $H_{max} = 1/a$. However, extrapolation like this can be misleading, and interpolation is always preferable to extrapolation.

Height-diameter relationship

To avoid the need to extrapolate the height-diameter relationship, the height at a nominated index diameter can be used as a measure of site productivity; it has been suggested that this measure be called site form (Vanclay and Henry, 1988) to avoid confusion with site index derived from the height-age relationship. The height-diameter relationship allows not only efficient evaluation of site in the field, but also the assessment of site from stereo aerial photographs by estimation from crown widths and tree heights measured on the photographs (e.g. Reinhardt, 1982).

McLintock and Bickford (1957) proposed anamorphic height-diameter equations based on dominant trees selected from stands from a wide range of sites, but not from stands with abnormal stocking or recent logging. Grimes and Pegg (1979) used hand-drawn height-diameter curves to characterize site quality in spotted gum and ironbark forests in Queensland. Neither study attempted to relate these curves to site index, but used the expected height at an index diameter as a measure of site productivity. Stout and Shumway (1982) and Lamson (1987) used height-diameter equations to predict site index compatible with published height-age equations. Their data were obtained from dominant and codominant trees, but taken only from even-aged stands. Reinhardt (1982) investigated several equations for the height-diameter-site relationship of western larch, and found that the relationship exhibited a strong polymorphic trend (Fig. 1)

$$H = 1.3 + 8.23 SI^{0.59} \times \left(1 - e^{-0.04DBH}\right)^{0.092SI}$$

where H is tree height (m), DBH is diameter (cm) and SI is site index (m) at 50 years.

Reinhardt (1982, 1983) worked with data from pure and mixed stands of western larch, and used the height-diameter curve to predict site index compatible with the height-age equations of Brickell (1970). Trees on better sites were taller than trees on poor sites, but this discrimination was not apparent until tree diameters exceeded 50 cm diameter (Fig. 1), and data from trees exceeding this size were necessary to establish a reliable estimate. Reinhardt (1983) claimed that the accuracy of the estimate depended upon the variability within the stand, but that reliable estimates could be achieved by measuring five to fifteen trees per plot. Vanclay and Henry (1988) adapted the method for use in the uneven-aged coniferous *Callitris* forests in Queensland, using the monomolecular or Mitscherlich equation (Fig. 2)

$$H = A - (A - 1.3)\left(\frac{A - S}{A - 1.3}\right)^{DBH/25} \qquad (1)$$

where H is tree height (m), A is the asymptotic stand height (m), A=-10.87 +2.46 S, and S is site form (m), the expected height of a 25 cm DBH tree. An adequate estimate of site form could also be obtained from a simple linear regression of height on diameter ($H = b_0 + b_1D$) for trees 20-30 cm DBH, and eqn. 1 was required only when trees of this size did not occur in the stand. Site form estimates for *Callitris* forests were relatively insensitive to logging, and remained constant over long periods of time (Vanclay and Henry, 1988). Logging may cause a perturbation in the estimate of site form for a few years, but the estimate will stabilize in a few years when the stand remains undisturbed. Site form is positively correlated with stand basal area increment, with diameter increments of individual trees (Vanclay, 1988a), and with several other indicators of site productivity (Table 2). Routine field application of this method suggests that best results are obtained in well-stocked monospecific stands.

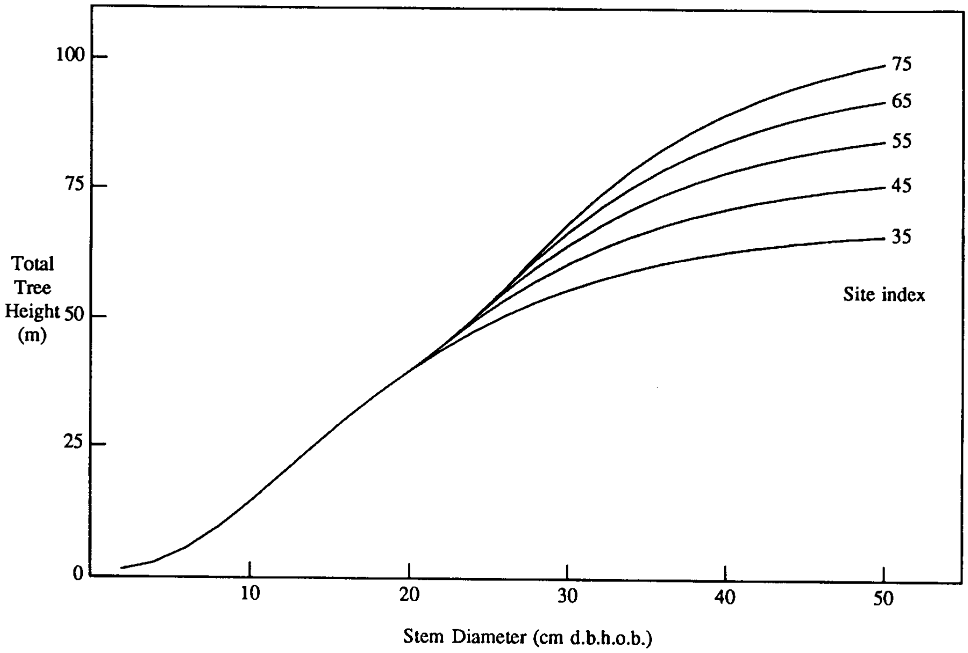

Fig. 1. Site index from the height-diameter relationship (Reinhardt, 1982).

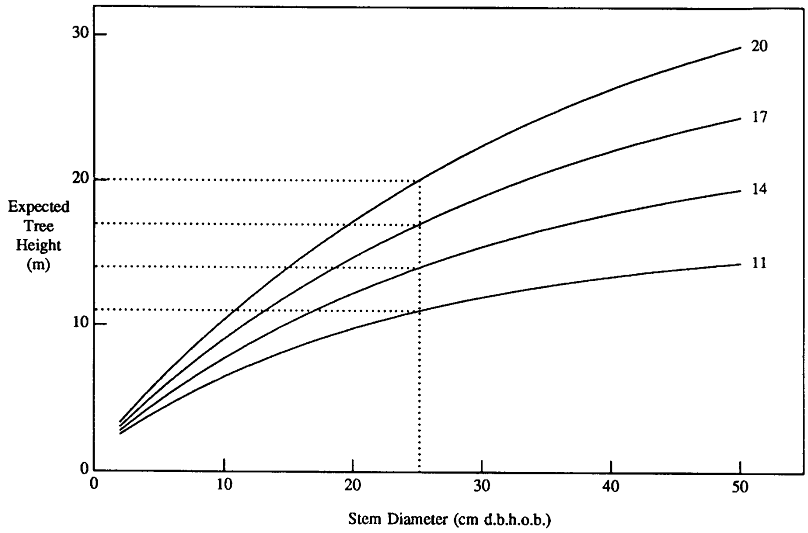

Fig. 2. Height-diameter equations for *Callitris* (Vanclay and Henry, 1988).

TABLE 2. Correlation coefficients between site form and site quality (Vanclay and Henry, 1988)

Indicators of site productivity	Site form (m)	Site quality (4 classes)
Subjective site quality (4 classes)	0.29	1.00
Maximum stand height (m)	0.70	0.40
Natural basal area (m^2 ha^{-1})	0.46	0.21
Mean annual volume increment (m^3 ha^{-1} yr^{-1})	0.40	0.34

The height-diameter relationship also showed promise as a measure of site productivity in mixed subtropical eucalypt forest in Queensland, and exhibited a strong correlation with volume production (e.g. 44 plots in *Eucalyptus* forest on Fraser Island in southeast Queensland showed a correlation of 0.77 between site form and periodic annual volume increment). The use of several *Eucalyptus* and other Myrtaceous species to estimate site form on any plot did not appear to influence estimates.

Some important conclusions regarding the approach may be drawn by analogy from site index research. Heger (1973) and Curtis et al. (1974) demonstrated the influence of index age on the precision of site index estimation. However, the circumstances are somewhat different for the height-diameter relationship, as many natural forests may be expected to have a large range of stem diameters. The height-diameter relationship can be determined with least error if the index diameter is within the range of diameters normally observed in the stand. Thus Grimes and Pegg (1979) used 30 cm in their study of *Eucalyptus* stands, and Vanclay and Henry (1988) used 25 cm as the index diameter for *Callitris* forests.

Site index equations are commonly used for two purposes, to predict the height growth of a stand of known site index, and to estimate the site index of a stand of known age and height. Bruce (1925), Strand (1964) and Curtis et al. (1974) demonstrated the importance of using the correct form of equation in regression analysis. The response variable about which the errors are minimized should be the variable of interest, in this case, height at the reference diameter. Some equations can be inverted and enable appropriate prediction functions for site form and for height to be formed. Parameters estimated for these alternative formulations usually differ (Monserud, 1984, 1985). Beck and Trousdell (1973) discussed sources of systematic error in determining site index equations, and their findings are applicable to the height-diameter relationship. The most common fault is to disregard possible age-site bias in sampling, and assume a constant curve shape on all sites. Beck and Trousdell (1973) stressed the need to ensure that the same sampling method used in establishing the equations should be used in their application. Other research into the development of site index equations is also relevant to the formulation of height-diameter equations (e.g. Lloyd and Hafley, 1977; Lloyd, 1981; Lloyd et al., 1982; Biging, 1985).

Volume production

Since volume production is usually the growth parameter of greatest interest to the forest manager, an evaluation of site productivity in terms of volume is desirable (Sammi, 1965). The Association of German Forest Experiment Stations agreed in 1888 to site classification based on volume at 100 years (Shrivasta and Ulrich, 1976). Sweden adopted a similar system in 1914 (Johnston et al., 1967), but since 1980 has estimated the mean annual volume increment (MAI) at culmination (U. Soderberg, personal communication, 1991). The Society of American Foresters (1923) recognized the superiority of a system based on MAI, but recommended that the use of site index based on height-age relationships was more convenient. The MAI cannot be measured directly for a single measure, but may be predicted from the heightage relationship.

The method of measuring volume must be standardized. Utilizable volume is inadequate because utilization standards vary in time and place. Estimates of sawn volume are even more unreliable (Wiant and Charlton, 1982). Assman (1961) recommended the use of solid wood (derbholz) volume defined as the volume under bark of all stem and branch material not less than 7-cm diameter under bark. This is convenient for conifers as it reflects the current utilization standards in common usage in many places. However, in trees with a deliquescent habit, this may entail the measurement of branch volume, which may be difficult. Weight has been used for pulp plantations in North America (Rennie, 1963). Others have argued for site productivity to be expressed as dry matter production in gravimetric units or calorific equivalents (Shrivasta and Ulrich, 1976).

Mean annual increment at culmination is a concept which applies only to an even-aged stand, but the periodic annual increment (PAI) is analogous in uneven-aged forests. Unfortunately, the complexities of the tropical moist forest are such that even the PAI is of little utility. Even if the solid wood volume, or some other suitable standard could be reliably determined, the difficulties of predicting this PAI from some measurable crop parameter remain. Volume MAI is meaningful in monospecific industrial plantations, but the tropical moist forest contains many species which may vary greatly in productivity and wood density. Biomass production (tonnes ha^{-1} year^{-1} dry weight) may provide a better basis for comparison. However, should the PAI refer to just one species, or to a specified mixture of species? In the tropical moist forest, an index of the site is probably more useful than an index of a species on that site. Notwithstanding this, the historic volume production of a well-stocked and well-managed forest provides a good measure of site productivity, and a good benchmark to validate other more easily obtained measures of site productivity.

Direct measurement of volume PAI requires measurement of permanent sample plots over many years. Schmoldt et al. (1985) attempted an alternative approach by fitting yield equations to permanent sample plot data, and examining both the maximum growth rate and the asymptotic volume. They found that aspect and soil nutrients were significantly correlated with asymptotic basal area, maximum basal area increment and asymptotic volume, but not with maximum volume growth rate or site index. They suggested that site index is unreliable in mixed northern American hardwood forests, and suggested that coefficients from yield equations fitted to permanent sample plot data may provide practical alternatives.

Growth index

Andel (1975) compiled a series of hand-drawn curves describing the basal area growth expected for a given stand basal area (about 20 m^2 ha^{-1}). His growth index indicated the expected basal area increment for a stand with the index basal area. Andel (1975) weighted the growth estimates to account for species composition of the stand in computing this index. Whilst this provides an indication of site productivity, it is liable to overestimate the site productivity for stands dominated by light-demanding and pioneer species, and underestimate site productivity of stands dominated by slower growing and shade-tolerant species.

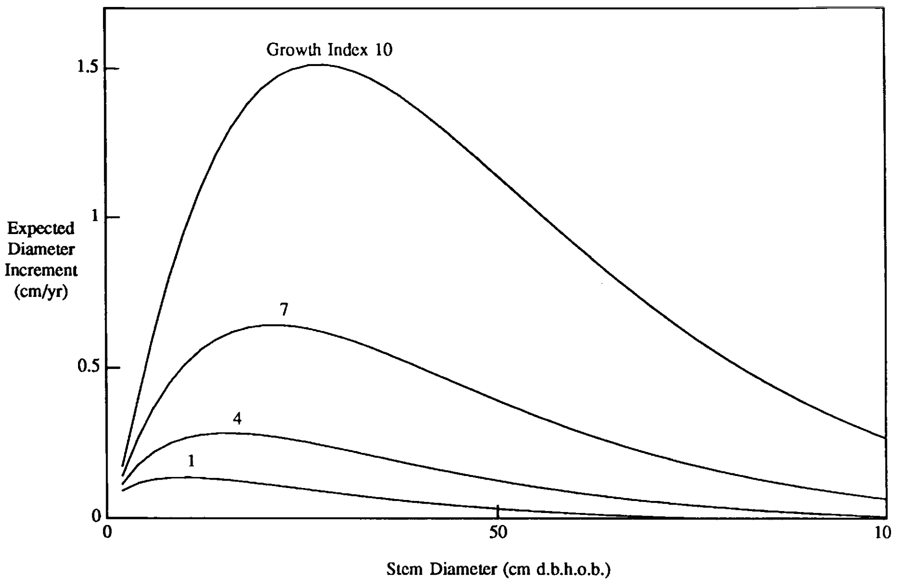

Fig. 3. Growth index equations for *Cardwellia sublimis* (Vanclay, 1989b): stand basal area, 30 m^2 ha^{-1}; overtopping basal area, 10 m^2 ha^{-1}.

Vanclay (1989b) developed an index of site productivity which accommodates a range of species and stand densities, does not require age or height, and avoids the problem with species composition in Andel's (1975) approach. The index was initially estimated from the historic measurement record for a number of permanent sample plots. Later, biotic and abiotic variables correlated with the index were used to predict the growth index for other sites and temporary plots. Vanclay's (1989b) index was based on the diameter increment of individual trees of several commonly occurring and widespread species. An increment function was fitted simultaneously to all species, with the plot identifier included as a qualitative variable (Fig. 3). Basal area was included to account for differences in stand density. Site quality was estimated from bioassay data

$$\mathrm{GI} = \frac{\sum_{ij}\mathrm{Log}(DI_{ij}+\alpha) - \sum_{ij}\left(\beta_{0i}+\beta_{1i}D_{ij}+\beta_{2i}\mathrm{Log}(D_{ij})+\beta_{3i}\mathrm{Log}(BA)+\beta_{4i}OBA_{ij}\right)}{0.08808\times\sum_{ij}\mathrm{Log}(D_{ij})} \tag{2}$$

where GI is the growth index of the plot; D_{ij} is the diameter (breast high or above buttress, over bark, in cm) of tree j of species i; DI_{ij} is its diameter increment (cm $year^{-1}$); OBA_{ij} is its 'overtopping basal area', the basal area of trees within the plot that are bigger than tree ij (m^2 ha^{-1}); BA is the plot basal area (m^2 ha^{-1}); and the βs are parameters estimated by linear regression.

This equation estimates growth index, a measure of site productivity based on the diameter increment adjusted for tree size and competition, of all trees of 18 reference species *(Acronychia acidula, Alphitonia whitei, Argyrodendron trifoliolatum, Cardwellia sublimis, Castanospora alphandii, Cryptocarya angulata, C. mackinnoniana, Darlingia darlingiana, Elaeocarpus largiflorens, Endiandra* sp. aff. *E. hypotephra, Flindersia bourjotiana, F. brayleyana, F. pimenteliana, Litsea leefeana, Sterculia laurifolia, Syzygium kuranda, Toechima erythrocarpum, Xanthophyllum octandrum)* using all available remeasures for the plot (except that where plots were remeasured more frequently, remeasurements were selected to achieve approximately 5-year intervals). The (βs were estimated by fitting the following equation simultaneously for all these reference species in the development data set (80 plots, a further 64 plots were used for validation studies)

$$\begin{aligned}\mathrm{Log}(DI_{ijk}+\alpha) = {} & \sum_{i=1}^{18}\beta_{0i}Spp_i + \sum_{i=1}^{18}\beta_{1i}D_{ijk}Spp_i \\ & + \sum_{i=1}^{18}\beta_{2i}\mathrm{Log}(D_{ijk})Spp_i \\ & + \sum_{i=1}^{18}\beta_{3i}\mathrm{Log}(BA_k)Spp_i + \sum_{i=1}^{18}\beta_{4i}OBA_{ijk}Spp_i \\ & + \sum_{k=1}^{80}\gamma_k\mathrm{Log}(D_{ijk})\,Plot_k\end{aligned}$$

where DI_{ijk}, D_{ijk} and OBA_{ijk} are the diameter increment (cm year^{-1}), initial diameter (cm) and overtopping basal area (m^2 ha^{-1}) respectively for tree j of species i on plot k; BA_k is the stand basal area (m^2 ha^{-1}) on plot k; Spp_i *is* a dummy (0, 1) variable which takes the value 1 for trees of species i and zero otherwise; $Plot_k$ is a dummy variable which takes the value 1 for trees on plot k and zero otherwise; and α, β_i and γ_k are parameters to be estimated. This equation can be expressed more compactly using GLIM notation (Aitkin et al., 1989):

$$\mathrm{Log}\,(DI+\alpha) = Spp + D.Spp + \mathrm{Log}\,(D).Spp + Log\,(BA).Spp + OBA.Spp + Log\,(D).Plot$$

where *Spp* and *Plot* are qualitative variables. The parameter α was assigned the value 0.02 after inspection of residuals and examining the residual mean squares from a range of values (Vanclay, 1989b). The value 0.08808 (in eqn. 2) was subjectively determined to scale the growth indices into the range 0-10. This procedure yielded unbiased estimates of site productivity (Vanclay, 1989b).

These procedures (Andel, 1975; Vanclay, 1989b) provide a descriptive measure of site, in effect an objective ranking of permanent sample plots, and do not provide a predictive measure which can be applied to temporary plots. However, the growth index can be predicted from other measurable or observable biotic and abiotic factors (Vanclay, 1989b).

ASSESSING SITE FROM PHYSICAL SITE PROPERTIES

One problem with the use of non-crop approaches to site evaluation is that they are usually used to predict the productivity of the site with respect to some crop property using regression analysis. Thus the utility of physical site properties to predict site productivity cannot be assessed directly, but is usually compared with some crop property (e.g. site index), which unfortunately is all too often inaccurate. This problem is evident in Grey’s (1979) attempt to relate site factors to site index. Grey considered three measures of site productivity, Marsh’s site index, Crowe’s site index and Wessels’ MAI, each of which was best predicted by a different subset of the site factors considered; no one factor was common to all three. This suggests that these three measures of site productivity were not sufficiently reliable to enable a consistent relationship to be established.

Climate

The best-known climatic index of forest growth is Paterson’s CVP index which was designed to predict the maximum growth potential in terms of volume production over large areas (Johnston et al., 1967). It is based on evapotranspiration, annual temperature range, mean annual precipitation, length of growing season and mean monthly temperature of the warmest month. Although it has been adopted on a national scale by a number of countries, it is probably only useful for economic geography and general forest statistics where estimates of potential production are required for large inaccessible and non-inventoried areas (Lemieux, 1961) . Similar indices of net primary production for global atmospheric studies have been based on evapotranspiration (Lieth and Box, 1972) and on temperature and precipitation (Esser, 1984).

Czarnowski (1964) developed an equation with three climate parameters, three soil parameters and four species properties to predict the productive capacity of a species independently of age, anywhere on earth. Trials with his equation indicate that predictions were close to observed values for three species on four continents. The model was subsequently refined to predict site index (at age 20) of *Pinus radiata* as a function of seven chemical and two physical soil characteristics, and three climatic variables, and achieved a mean error of about 10% (Czarnowski et al., 1976). However, this equation lacks the general utility of Paterson's CVP index, and involves considerable effort in determining soil nutrient status.

Degree-days (number of days during which the mean temperature exceeds a specified temperature, usually 5 or 10 0'C) and precipitation during growing season have been used to estimate site productivity (e.g. Farr and Harris, 1979). The distribution of the rainfall is probably more important than the actual amount (Jackson and Gifford, 1974; Jackson et al., 1975). In temperate regions, rainfall during the growing season is important, whilst in the seasonal tropics dry season rainfall may be critical. These variables may be used directly, or predicted as a function of latitude and altitude.

Topography

Climatic variables can only give a general indication of site productivity because they fail to account for any local variations in site. An obvious refinement is to include topographic information relevant to the specific site. An advantage of using only climatic and topographic information is that these details can be readily obtained from topographic maps (or air photos) and climatic records. In areas of marked relief, topographic effects may be the dominant force controlling site productivity (Ralston, 1964; Malcolm, 1976). Evans (1974) found that height at age 12 years in *P. patula* plantations in Swaziland was highly correlated with altitude. Monserud (1988) found altitude and habitat type were the best predictors of site index in irregular Douglas-fir stands in North America. Site index of upland oaks in southeastern Ohio can be predicted with reasonable precision from aspect, slope shape and position on slope (Carmean, 1967). Stage (1976) demonstrated the interacting effects of slope and aspect on the site index of white pine, and suggested a technique to locate the favoured aspects. This procedure is implemented in Wykoff's (1990) increment functions for temperate coniferous forests. Vanclay (1989b) found that total annual rainfall, altitude, slope and aspect were not significantly correlated with the growth index of tropical moist forest in Queensland, but did not examine annual rainfall distribution. In many areas, the distribution of the rainfall may be more relevant than the actual amount.

Most investigations into the relationship between topography and site quality have used simple variables such as altitude, aspect and slope. Whilst these have produced some promising results in temperate forests, their predictive ability has not been demonstrated in the tropics or subtropics. In an analysis of vegetation types in Australian temperate forests, Moore et al. (1991) found that "steepness" (the diversity of elevation within a 200-m region, indicative of erosional/depositional environment) and "exposure" (the average angle to the northern horizon, indicating shading by the topography) provided better predictions than slope and aspect. Vertical height above the nearest stream also provided good discriminations, better than the conventional position on slope (D.M. Moore, personal communication, 1991). This suggests that there remains scope for further research in this area.

Soils

The next logical step in refining the estimation of site productivity from physical characters is to include information about the soil. However, complications quickly arise. Soil depth, colour and texture are easily determined, but determination of nutrient concentrations requires laboratory analysis, and there is no satisfactory way of quantifying soil water supply on a single visit. Furthermore, soil nutrient concentration need not reflect the availability to forest trees, and may change seasonally. Despite these difficulties, numerous studies involving soil analysis have been made. Carmean (1973) listed 793 publications dealing with forest soils in the north-central states of the USA, some of which report reliable estimates of site index from soil nutrient concentrations. Mader (1976) found site index and periodic annual volume increment of white pine strongly correlated with several topographic and soil physical and chemical variables. Site index was only weakly correlated with topographic and simple soil physical properties, and topographic variables alone were not significant. In contrast, Fralish and Loucks (1975) found that including soil nutrient data only slightly improved site index estimates for aspen. Grey (1979) failed to find any significant correlation between *P. patula* site index and a number of soil morphological and chemical features. However, topographical features such as land surface class, slope, altitude and distance from ridge crest were significant. Schonau and Aldworth (1991) found that effective rooting depth was the most influential variable in predicting site index of black wattle plantations, but that phosphorus, potassium and organic carbon content of the topsoil were also significant.

Jackson and Gifford (1974) and Hunter and Gibson (1984) found that productivity (volume increment and site index respectively) of *P. radiata* plantations could be estimated from rainfall and soil chemical and physical characteristics. Truman et al. (1983) found that site index of *P. radiata* plantations could be predicted from foliar nutrients (phosphorus and calcium) as well as from soil nutrients, but both approaches require expensive sampling and laboratory analyses. The relationship between foliar nutrients and site productivity is likely to be species-dependent. Mijers (1937) found no clear relationship between the chemical composition of forest soils in Indonesia and teak site quality classes, but found that site might be evaluated from soil physical conditions.

Wright and van Dyne (1971) studied 50 equations predicting site index from physical site factors for several species in different regions of the USA, but found it difficult to generalize on the most important variable. On poorly drained sites, texture and depth to impermeable layers were crucial, and on other sites, topography, available water and soil depth (total depth, effective depth or depth of A-horizon) were important. Carmean (1979a) suggested that important soil features include surface soil depth, depth to mottling, depth to impermeable layer, effective soil depth, texture and stone content, structure, drainage and subsoil colour. Schmidt and Carmean (1988) reported that soil depth, stone and clay content, slope and subsoil pH were significant in predicting site index of P. *banksiana.* Shrivasta and Ulrich (1978) and Vanclay (1989a,b) found that stratification of sites according to geological formations increased precision of site productivity estimates.

Webb and Tracey (1967) found that site index of *Araucaria cunninghamii* could be predicted from surface geology and land form, within broad climatic zones. Soil mineral status was the dominant factor. Acid rock produces soils of low fertility, while more basic parent material yields soils of high nutrient status. Slope, soil depth and texture and the presence of a clay subsoil with impeded soil drainage were also important factors. Webb (1969) reported that simple measurements of soil depth and aeration and total amounts of the major inorganic nutrients, could enable reasonably accurate estimates of site productivity to be made. The soil mineral status may be deduced from surface geology, or inferred from the structure of the forest.

Baker and Broadfoot (1977) devised a scheme to determine site index based on the contribution of a number of factors towards the height at index age. They used five physical soil properties, eight moisture parameters, six factors reflecting nutrient availability and four factors concerning aeration, all of which were easily assessed in the field. The method assumes that each factor is responsible for a certain percentage of tree growth, and that there is limited interaction between factors.

Turner et al. (1990) formulated a soil classification for industrial *P. radiata* plantations, designed to reveal potential nutritional deficiencies and other management limitations from physical soil parameters that did not require laboratory analysis. The system was based on characteristics that indicated innate nutrient supply, the development of roots, moisture supply, and other growth and management factors, and included parent rock, texture profile, depth to and nature of impeding layer, texture and condition of the uppermost 10 cm of soil, character of horizons and the condition and colour of the subsoil. Parent rock sets upper limits to the total amounts of clay, primary quartz and many plant nutrients that can be released through mineral weathering (Brewer, 1954), and Turvey et al. (1990) found that parent rock, and depth to and nature of impeding layer explained most of the variation in wood volume production. Parameter estimates from their equation could be summed to provide estimates of wood volume production at age 11 years. The Turner et al. (1990) soil classification system provided better estimates of productivity than did other more widely used classifications.

ASSESSING SITE FROM VEGETATIVE CHARACTERISTICS

Many site properties such as available water and nutrient concentrations are not easily measured, so an alternative is to measure indicative variables such as composition of ground vegetation. No causal relationship is implied, but it is assumed that both ground vegetation and timber production are influenced by the same properties. Lowry (1976) studied many physical site characteristics, only to conclude that the native vegetation appeared to be the best indicator of site productivity. Daubenmire (1976) concluded that vegetation reflects the sum of all the elements of the environment which are important to plants, and established six basic principles arguing for vegetation as the best method for assessing site productivity: (1) vegetation reflects the sum of all the elements of the environment which are important to plants; (2) the species with the highest competitive powers are the best indicators; (3) forests consist of superimposed groups ('unions') which occur in different combinations over the landscape; (4) each union is sensitive to certain special aspects of environment; (5) many characters of vegetation have potential significance as ecologic indicators; (6) types of environment ('habitat types') are the most basic ecologic units of landscapes.

Two main approaches can be distinguished: the classification approach (also known as subdivision, European or Braun-Blanquet) which uses the (potential) climax vegetation, and the ordination approach (also known as the Anglo-American or Clements) using indicator plants. Regions may also be stratified or classified on the basis of land form or other characteristics (e.g. Smalley, 1986), and this procedure should not be confused with the BraunBlanquet classification of vegetation.

Classification

This approach to site evaluation has several schools, each pursuing a variation of this theme (Havel, 1980a,b). However, all use the potential climax vegetation to classify areas into a number of habitat or site types, which are considered to be effectively uniform in many respects. The classic example of floristic classification for site evaluation is Cajander's use of various associations of ground vegetation to predict site productivity in Finland (Rennie, 1963). This approach has been used with only minor modifications in Europe and North America.

Ure (1950) applied such a system in New Zealand, and was able to derive a satisfactory and rapid estimate of *P. radiata* site class from his habitat types. He cautioned that for the system to work, the vegetation must not have been burnt, ploughed or otherwise interfered with. The sides of roads should also be avoided. In a similar study, Daubenmire (1961) found that floristic classification was a useful and rapid method for predicting height growth and disease susceptibility of *P. ponderosa* in the USA. Waenink (1974) found a slight correlation between forest floor vegetation (i.e. habitat type) and growth of Japanese Larch, which improved when watertable classes were also considered. He also found a strong correlation between forest floor vegetation and the history of phosphate fertilizer application.

Webb (1959) developed a classification' scheme based on the physiognomic characteristics of Australian rainforests. Webb et al. (1970) subsequently proposed a more sophisticated approach based on physiognomic and structural characters. This approach was found to be as effective as the more common floristic approach to classification in indicating environmental conditions. One advantage of using structural features is the ease and speed of data collection. The approach also appears to have greater applicability over diverse geographic regions. One shortcoming is that structural features are generally defined in an informal manner, and delineation of habitat types is not necessarily unique especially when prepared by workers not familiar with the approach (Webb et al., 1970). However, Vanclay (1989b) found no correlation between growth index and the Webb et al. (1970) classification.

Pfister and Arno (1980) and Pfister et al. (1977) discussed possible applications of their habitat type classification for Montana. One danger in shifting emphasis from assessing forest site productivity to a system which fulfills broader multidisciplinary objectives is that in doing so, the value of the classification for site assessment may be reduced. However, Monserud (1984) found classification into habitat types useful, enabling site index curves of different shapes to be prepared for each type. Classification may provide accurate estimates of site productivity when developed specifically for the purpose, but more general approaches that can be used for a variety of purposes may not predict the site productivity so well (Jones, 1969). One problem with classification is that it remains an imprecise science. Ecological and other non-mathematical classifications are unavoidably subjective, whilst the outcome of mathematical approaches depends largely on the algorithm chosen. Of the many algorithms available, only single linkage cluster analysis emphasizes the separation of clusters; other algorithms may maintain clusters without regard to the possibility that two similar units may be assigned to different major clusters (Gower, 1967; Jardine and Sibson, 1971; Sneath and Sokal, 1973).

Ordination

Two approaches to ordination exist. The first and most widely utilised is to use the presence (and occasionally abundance) of certain plants as an indication of site productivity; the other uses physiognomic characters such as size and shape of leaves, and the height of the indicator plants. These methods are not mutually exclusive, and may be used in conjunction with each other (Hagglund, 1981) . The presence and abundance of each plant indicator expresses a set of environmental conditions favourable to that species. A community of such plants may express much of the biologically relevant factors and interactions of the site. Thus the use of indicator plants comprising a community may express the integration of factors more flexibly than the climax vegetation approach (Jones, 1969). Webb et al. (1967, 1971) found that classification failed to give a sensitive indication of site productivity and that ordination could reflect environmental factors with much greater precision. Havel (1975) found ordination more appropriate than classification, and obtained the best results when all very rare and very common species were excluded from the ordination analysis. Hodgkins (1960) and Corns and Pluth (1984) gave regression equations incorporating the presence and abundance of several plant species to predict site index of natural conifer stands. However, Griffin (1967) reported that the abundance of indicator plants is likely to be influenced by disturbance, whilst presence or absence is more stable.

MacLean and Bolsinger (1973a) and Wiant et al. (1975) gave equations to predict site index from the presence and absence of several indicator plants. Most of the indicator plants could be found even after drastic disturbance. In a similar study, Dyrness (1973) found indicator plants remarkably persistent, even after clearfelling and burning. Webb et al. (1971) found that site productivity could be reliably determined from suitable indicator plants even after clearing and several years of management. Webb and Tracey (1967) also gave lists of pioneer species which indicate good and poor sites for hoop pine plantations. This is consistent with Daubenmire and Daubenmire’s (1968) observations that the presence of ground flora was largely independent of the overstorey. However, indicator species need to be chosen carefully, as even apparently stable rainforest may have a relatively high species turnover rate (Poore, 1968). Swaine et al. (1987) reported a species turnover of around 1% year^{-1} in undisturbed tropical moist forest. However, indicator species in tropical moist forests may not be greatly influenced by disturbance, as Stocker (1981) reported that 82 species returned within 2 years after felling and burning of a tropical moist forest in Queensland. Webb et al. (1967) and West et al. (1988) reported that both soil moisture and fertility affected species occurrence.

Carleton et al. (1985) examined the influence of temporal factors such as stand density and succession on understorey vegetation in northern Canada, and found that these have minimal influence on vegetation. They found that the understorey vegetation was most influenced by soil, and concluded that the understorey vegetation should provide a reliable indicator of site quality. However, Schonau (1987) considered the use of plant indicators more useful in temperate regions where there are fewer species, and concluded that vegetation on its own is generally not suitable to determine site quality satisfactorily. Vanclay (1989b) found that the growth index of a tropical moist forest in Queensland could be reliably predicted from the presence of several tree species. If the correct taxonomy of indicator trees was known, geology contributed no further improvement. However, exact identification of rainforest trees is often difficult, and a single common name may refer to more than one species. Good estimates of growth index could be obtained if geology was used in conjunction with common names:

$$GI=\begin{pmatrix} 4.528\times AL \\ 5.934\times BV \\ 5.164\times AV \\ 6.174\times CG \\ 4.980\times SM \\ 3.837\times TG \end{pmatrix} \begin{matrix} +1.144\times BLO+1.286\times SBN-1.020\times VTX-0.673\times RAP \\ +1.027\times BUA+1.008\times RBN-1.223\times CLL+1.516\times BGR \end{matrix}$$

where all variables are dummy (0, 1) variables which take the value 1 if the geology or species is present on the plot, and 0 otherwise; *BLO is* blush silky oak *(Bleasdalea bleasdalei* and *Opisthiolepis heterophylla); SBN* is salmon bean *(Archidendron vaillantii); VTX* is vitex (*Vitex acuminata); RAP* is rapanea *(Rapanea achradifolia); BUA is* buff alder *(Apodytes brachystylis); RBN is* rose butternut *(Blepharocarya involucrigera); CLL is* cinnamon laurel *(Cryptocarya cinnamomifolia* and some affiliated species); and *BGR is* brown gardenia *(Randia fitzalanii);* and where the geology *AL is* alluvial, *BV* is basic volcanic, *AV* is acid volcanic, *CG* is coarse granite, *SM* is sedimentary-metamorphic, and *TG* is Tully fine-grained granite. Note that whilst the various geology types are mutually exclusive, any number of species may be present and used to evaluate the growth index. None of these species are shortlived pioneer species, and the presence/absence of these species should be relatively independent of successional status and disturbance.

Keenan and Candy (1983) used the principal components of a presence/ absence (1,0) matrix in which 1 indicated that the species (ten species or groups) occurred over at least 30% of the plot area (0.0 1 ha) covered by noneucalypt vegetation. The ten species groups were derived by omitting species which occurred on fewer than three of the 52 plots, and amalgamating some less-frequent genera. Matrices comprising presence/absence (any occurrence of 28 species) and percentage cover data provided similar but inferior results. Principal components offer some advantages for investigation: they provide more than one linear combination of the (0, 1) data and can thus reflect more than one environmental gradient, and component correlations of the principal components are unchanged by adding or subtracting other explanatory variables to the model (Keenan and Candy, 1983). However, one disadvantage is that principal components are specific to each set of data: additional data may give rise to different principal components, and thus subsequent studies and predictions must use the original component correlations. Keenan and Candy (1983) found that the first principal component explained 29% of the total variation, more than the non-floristic site factors (slope, altitude, exposure, soil parent material, soil pH, soil drainage) which, although significant ($P<0.01$) collectively explained less than 9% of the total variation. Principal components 7, 8 and 10 were also significant. Keenan and Candy's (1983) analysis suggested that plant species were better predictors of height growth than human appraisals of non-floristic factors.

PRACTICAL CONSIDERATIONS

Mapping site productivity using remote sensing

Forest-type mapping has been prepared from remote sensing for many years, and broad site quality classes can often be defined. Aerial photographs may allow objective measurement of some measures of site productivity. Bonnor and Morrier (1981) used aerial photography to classify temperate mixed forest in Canada into 5-m site index classes with 76% success: the remaining instances underestimated by one class. Goodwin (1988) reported the use of aerial photography to determine mature stand height in temperate *Eucalyptus* forest in Tasmania. Aldred and Bonnor (1985) suggested that airborne lasers may be useful for mapping stand height. However, all these methods require the ground to be sighted through the canopy, and may be impractical in tropical moist forests.

Digital remote sensing from satellite (e.g. Landsat) offers potential for objective algorithm-based site productivity mapping. Fox et al. (1985) reported that broad site quality classes could be estimated from aspects derived from digital topographic data combined with vegetation classes obtained through supervised classification of Landsat data. Vanclay (1989b) and Vanclay and Preston (1990) reported that growth index could be estimated directly from Landsat TM (Thematic Mapper) data and geology, although prediction equations may need to be re-calibrated for each Landsat scene. Vanclay and Preston (1990) found that the ratio of band 4 (and band 5 (mid-infrared) provided reasonable estimates of growth index, especially when used in conjunction with geological data:

$$GI=\begin{pmatrix}15.75\times AV\\ 18.13\times BV\\ 18.42\times CG\\ 17.59\times SM\end{pmatrix}+3.017\times\frac{TM_4}{TM_5}-0.284\times TM_1$$

where *AV, BV, CG, SM* are dummy (0, 1) variables representing acid volcanic, basic volcanic, coarse grained granite and sedimentary-metamorphic geology respectively, and where TM_1, TM_4 and TM_5 are the blue, near-infrared and mid-infrared Landsat TM bands respectively. However, this equation should be re-calibrated for each image, and could not be extrapolated to other passes. Oza et al. (1989) also found seasonal difference in the prediction of stand variables in teak plantations from Landsat multispectral scanner data.

Mapping site productivity using geographic information systems

Geographic information systems have become an important and useful tool in forest management, and offer some potential for mapping site productivity. Several studies (e.g. Austin et al., 1984; Moore et al., 1991) have demonstrated the utility of these systems for mapping vegetation types, and these studies suggest potential for mapping site productivity. Turvey et al. (1990) found that soil parent material and soil depth were the primary determinants of *P. radiata* site productivity. Suitable soil parent material classes can be derived from published geological maps, whilst soil depth may be inferred from a digital elevation model. Moore et al. (1991) found that steepness was easily calculated with a digital elevation model and indicated erosional and depositional areas which may serve as a suitable proxy for soil depth.

Multiple estimates

Different methods of site productivity assessment may give rise to differing estimates, and the forest manager may have no basis for resolving these differences. Choosing the most popular or well-established technique is one alternative; others may include choosing the method which intuitively seems right, or taking the mean or median of all available estimates. If permanent sample plot data are available, the alternative techniques can be tested using standard procedures (e.g. Freese, 1960; Reynolds, 1984), but where no such data are available, the 'true' value cannot be determined and alternative selection procedures are required. Reed and Jones (1989) suggested an objective approach based on the multitrait-multitemporal approach of the psychometric literature (Campbell and Fiske, 1959) to reconcile different estimates of forest productivity. The method involves conceptualizing the relationships among the estimates, standardizing these estimates, calculating correlations and identifying correspondences between the approaches. The most consistent approach is assumed to be the most reliable.

Changing species of estimation

Where a crop parameter is used as a measure of site production, it may refer to a specific species in the crop, or to a stand of specified composition. It may be possible to gauge the potential of a site for another species or composition by a transformation of the measured parameter. Another application of this technique is that it enables extensive areas of mixed forest to be evaluated in terms of one standard species, even if that species is not present over the whole area.

Foster (1959) found a curvilinear relationship between the site indices of eastern white pine and red maple, and found that red maple exhibited rapid early height growth and could be expected to exceed the height of white pine until the age of 46 years, when the trend reversed. Red maple was more sensitive to site, being taller on good sites and shorter on poor sites, than white pine. McQuilkin (1974) found that site indices of black, scarlet and white oaks differed by simple constants across a wide range of sites. Carmean (1979b) used linear relationships to convert site index estimates between 13 species of northern hardwoods in the USA. Steele and Cooper (1986) used linear relationships to compare site index estimates for nine species of conifers in USA. All were positively correlated with slopes varying from 0.3 to 1.8 and intercepts varying from - 13 to + 14 m.

Shoulders and Tiarks (1980) examined the influence of rainfall, slope and available soil moisture on the height at age 20 years of four species of pines indigenous to that part of the USA Gulf Coastal Plain. They found, that the relative heights of the species were affected by these three characteristics. Where the annual rainfall was less than 1300 mm, P. *echinata* was tallest, and where more rain was received, either *P. elliottii* or *P. taeda* was taller, depending on soil, slope and the distribution of the rainfall. *Pinus taeda* grew best where the cool-season rainfall and the warm-season rainfall were each less than 650 mm. As the warm-season rainfall increased and the cool-season rainfall decreased, *P. elliottii* exhibited an advantage over the other species.

Equations comparing site indices may be useful for assessing the potential performance of species on sites where they are not present. However, care should be taken with interpretation, as most comparisons published to date compare only the height at index age. Such comparisons should be made only after comparing the methods of determining site index for both species, and comparing the shape of the height-growth curves.

All these studies reveal a positive correlation between species-specific estimates of site productivity across various sites. A site which is better for species A is also better for species B, but not necessarily by the same amount. Because of the differing growth habits of various species, comparisons of height or site index based on different species may not give a reliable indication of the timber production potential of various sites. Periodic annual volume increment realized under a specified management regime may provide a better basis for comparison.

Uniformity of site

A further complexity in assessing the potential productivity of sites arises where the site is not uniform, but is perforated by physical obstructions such as rocky outcrops. An insidious feature of this phenomenon is that conventional measures of site such as site index indicate the potential of the better pockets, and fail to indicate the true average productivity of the site. However, top or predominant height is often determined as the mean of the tallest tree on each of several adjacent non-overlapping plots, and this should reduce bias from such phenomena.

MacLean and Bolsinger (1973b, 1974) proposed the use of stand density index (Curtis, 1970), predicted from indicator plants to adjust yield estimates. An alternative approach is to examine the physical attributes of the site and determine an arbitrary reduction, but this approach is not without difficulty (MacLean and Bolsinger, 1973b).

CONCLUSION

This review has compartmentalized the many options available for site evaluation into discrete categories. This is convenient for reviewing and comparing the different options, but irrelevant in application. It is likely that the best approaches to site evaluation may employ a combination of several of these options (e.g. Lewis et al., 1976.). The development and evolution of an efficient method of site evaluation for tropical moist forests will rely on comparisons of alternatives with long-term growth recorded on permanent sample plots. Indices such as growth index (Vanclay, 1989b) show promise, but in practice would normally be estimated from stand and environmental variables, including indicator species. Measures of stand height such as maximum stand height, canopy height and the height-diameter relationship may also prove useful, but should be tested against the criteria of Vanclay and Henry (1988): reproducible and consistent over long periods of time; indicative of the site, and not unduly influenced by stand condition or management history; correlated with the site's productive potential; and at least as good as any other productivity measures available.

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