PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B BIOLOGICAL SCIENCES

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Phil. Trans. R. Soc. Lond. B 1975 **271**, 139-148
doi: 10.1098/rstb.1975.0040

Phil. Trans. R. Soc. Lond. B. **271**, 139–148 (1975) [139]
Printed in Great Britain

The use of bole surface in the estimation of woodland production

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The biological potential for timber production is defined as the accumulated fractions of net primary production expected to become timber. It is proposed that the timber fraction of ecosystem production can be expressed as a matrix of primary units of measure. The primary matrix is a set of values for volume, bole surface, and length arrayed by top diameters of stem segments and aggregated from the largest to the smallest. From this matrix one may estimate the potential production of a multitude of timber products. It is proposed that this primary matrix also is practical for estimating biomass, energy, water and nutrient flows, and the distribution of organic matter among trees, shrubs, and herbaceous plants. These relations can provide a basis for practical choices among alternative silvicultural actions and for estimating how much organic matter can be harvested as a crop in relation to other forest goods and services.

The concept of ecosystems was originally put forward by Tansley (1935) to encompass the complex interrelationship of the physical and chemical environment of plants, animals and people. Silviculture is applied to forest ecosystems for the production of many kinds of goods and services (Ovington 1962; Spurr & Barns 1973). Although research on the process of forest ecosystems has already considered problems of total organic matter production, partitioning of organic matter and flow of energy, nutrients and water for many experimental locations (Anonymous 1971; Young 1967, 1973*b*; Whittaker & Woodwell 1971; Reichle 1970; Duvigneaud 1971; Worthington 1971), the knowledge gained has not yet been used in silvicultural practices.

The interest in harvesting large amounts of organic matter in addition to timber emphasizes the need for a knowledge of ecosystem processes in practical silviculture. Plans to use leaves, understory woody plants and litter for fibre and fuels (Chase, Hyland & Young 1973; Koch 1973; Szego & Kemp 1973) and photobiological energy (Hall 1974) could strongly influence the productive potential of the site by modifying processes in the ecosystem (Ovington 1968; Duvigneaud & Denaeyer-De Smet 1970) in a detrimental or beneficial manner with respect to continued production. It is important for forest managers to have some understanding of the processes of the ecosystem.

Most of the above-ground biomass of a forest is in trees and most of the organic matter harvested is timber. A change in the timber fraction of biomass directly or indirectly affects most activities of the ecosystem. Moreover, the total biomass of an ecosystem can be approximately estimated by measurement of the timber component by non-destructive means. Indeed measurement of increase or decrease of timber biomass approximately measures changes in primary production of forest ecosystems.

Timber as a fraction of ecosystem production

In forestry practice the biological potential for timber production is the amount of timber, limited only by biological constraints, that can be expected in a given time with specified silvicultural practices. The relationship of the biological potential for timber production to ecosystem production is generalized in figure 1. The total organic matter formed by photosynthesis and nutrient assimilation is gross primary production. Net primary production is the organic matter left after green plant respiration. The proportion of net primary production accumulated as timber is limited by essential needs for leaves, reproductive organs, roots and small branches. Within the ecosystem organic matter is also diverted from timber production into non-timber plants and into material utilized by animals, micro-organisms, fire and other agents. It is the regulation of net primary production that offers practical opportunities for intense culture of forests as whole systems.

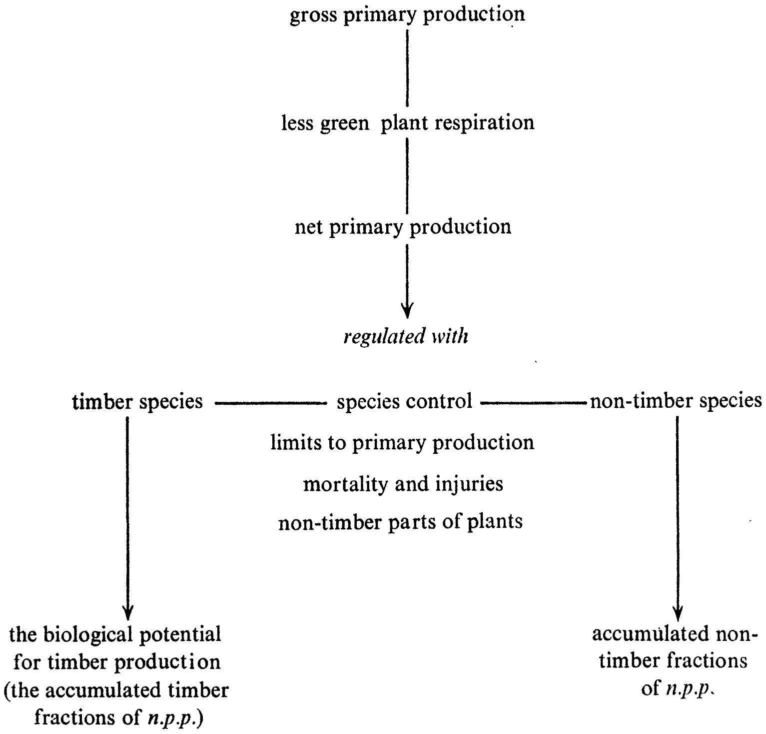

Figure 1. The relation of the biological potential for timber production to ecosystem production. Arrows indicate potential partitioning of organic matter.

Ecosystem production influenced by silviculture

The most important way to influence ecosystem function for management objectives is to regulate which species are to contribute to net primary production. Regeneration, overstory density, weediness, and type and time of harvest can for instance be controlled. In this way the relative proportion of timber and non-timber species can be affected and because other aspects of ecosystem function are changed the proportion of net primary production going into timber may be changed.

It is not yet practical to increase the upper limit of net primary production, which is about 2 % of the photosynthetically active radiation. However, some silvicultural techniques tend to keep the rate of photosynthesis near its upper practical limit and direct productivity to desired species. Short rotations, nutrient applications, changes in availability of water, removal of competition together with selection of desired genotypes of timber species may all have such an effect. (Saucier, Clark & McAlpine 1972; Wareing & Mathews 1971; McKee & Shoulders 1974). In addition, protection from insects, disease and fire may also influence forest production.

Harvesting of organic matter in non-timber parts of plants (Chase *et al.* 1973; Koch 1973) can increase the proportion of net primary production used although it does not alter the total. In a similar way techniques changing the form of trees by diverting organic matter from roots to bole (Harris, Goldstein & Henderson 1973) have been considered. Since leaves, branches and roots contain proportionally more nutrients than timber (Stone 1973; Ovington 1968; Duvigneaud & Denaeyer-De Smet 1970), use of them may lower the long-term production of the ecosystem. In addition, the cost of harvesting small volumes with large surfaces and lengths must be considered. It is impractical to measure net primary production directly for all combinations of environments, genotypes and silviculture (Whittaker & Woodwell 1971; Young 1973*a*). We can, however, measure timber using units that may be converted or related to a multitude of timber products and can be correlated with indicators of net primary production and functions in forest ecosystems. Board feet,† cubic metres, biomass, basal area, linear metres, etc., used singly are not suitable.

Grosenbaugh (1964) proposes using three units of volume, bole surface and length for forest inventory and for conversion to a multitude of timber products. These units are receiving increased attention in forestry (Bruce 1970; Stage 1973; Space 1973, 1974). As pointed out by Grosenbaugh (1964), the trio of measurements are in terms of relatively invariant, reproducible primary units of measure that tend to reflect sizes of trees and to be linearly related to the product of each manufacturer, regardless of what product he makes or what processes he uses. The units are particularly suitable for linear programming. With appropriate coefficients they may be used to estimate mass and thus biomass.

It is proposed that these three primary units can be used in a matrix for interrelating ecosystem production and silviculture. Grosenbaugh (1954) demonstrated the utility of such a matrix in connexion with a specialized type of dendrometry and quality assessment for timber. Height-accumulation was an important part of the technique.

Timber potentials expressed by a primary matrix

The complete primary matrix is a set of values for volume, surface, and length (*VSL*) arrayed by top diameters of stem segments and aggregated from the largest to the smallest stems. One can visualize the primary matrix as all of the boles, stems, and branches of a forest being suspended by their tips from a horizontal straight line and with selected points of equal diameter connected (figure 2). *VSL* of stem segments are totalled by diameter classes and accumulated from the largest to the smallest diameter (table 1). In practice, only the larger stems and tree boles are measured and the understory shrubs are measured only as required.

Relative density is a fourth desirable unit of measure in the primary matrix but inclusion must wait for the development of ways to measure relative density directly for standing trees. Average relative density and masses for whole trees ard merchantable lengths have been estimated by regression methods from diameter at breast height (d.b.h.), age, height and the

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† 1 board foot ≈ 2.36×10^{-3} m^3.

relative density of increment cores (Wahlgren & Schumann 1972; Maeglin 1973; Burkhart & Clutter 1971). Grosenbaugh (1967) suggests joint functions that include the ratio of surface to volume.

The primary matrix partitions trees of the same species or genotypes into classes of bole segments of progressive top diameters. This grouping tends to stratify variations in specific gravity by age, height, distance from the pith, and rate of growth (figure 2). Regression equations stratified by species and geography with elements of the primary matrix as independent variables, should give more reliable estimates of relative density and biomass than regression estimates based on d.b.h., and height.

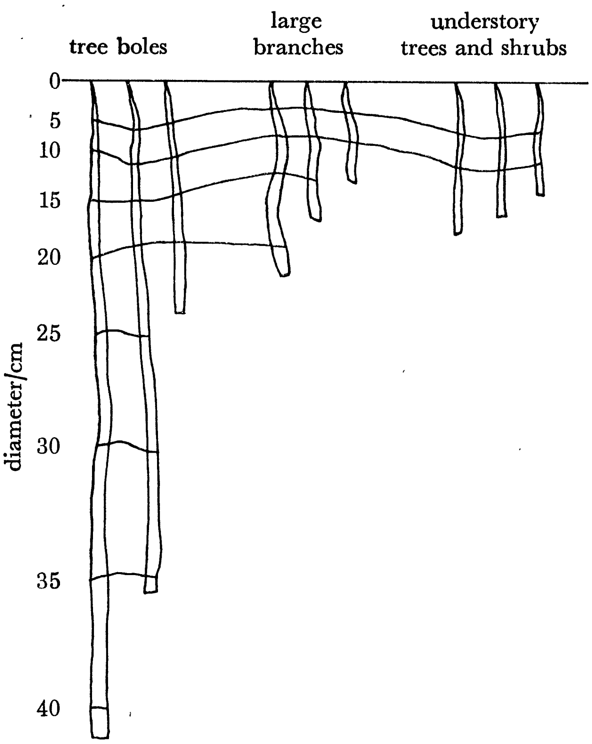

Figure 2. Examples of boles and branches with 5 cm intervals of diameter connected. Volume, surface, and length values are summed by diameters to form the primary matrix.

Table 1. Example of a primary matrix for 5 cm intervals of diameter outside bark and to a minimum top diameter of 10 cm (computed from data collected with a dendrometer in a stand of oaks)

diameter outside bark/cm	volume m^3/ha	surface m^2/ha	length m/ha
10	106.9	1596.4	1720.4
15	102.9	1291.6	1264.1
20	93.4	1099.8	1082.8
25	85.4	943.4	906.0
30	73.3	771.2	712.8
35	34.0	287.7	232.7
40	10.6	90.0	60.6
45	7.0	51.5	31.0
50	3.0	18.0	9.0
55	2.2	12.0	5.5

Biomass has usually been estimated by felling sample trees and extending measurements of them to a population by regression. Most of the techniques and limitations are discussed by Whittaker & Woodwell (1971) and Young (1973*a*). Green and dry mass yield tables have been made by regression (Burkhart & Clutter 1971; Lenhart 1973). Guttenberg & Fasick (1973) have shown how to estimate veneer and lumber yields from the number and mass of logs entering the mill yard. Different mills can develop mass-scaling conversion tables to meet their particular needs for processing, inventory, and allocation of raw material (Tyre, Fasick, Riley & Lege 1973). Elements of the primary matrix could possibly be used as independent variables in regression to relate timber products at mills to silviculture and ecosystem production without the use of volume and mass yield tables.

VSL is being used for timber inventories (Van Hooser 1973; Space 1973), but complete primary matrices have not been made for large forested areas. Only recently has it been possible to accurately measure *VSL* of standing trees. Accurate and easily used dendrometers (Grosenbaugh 1963) and the associated computer programs (Grosenbaugh 1971) makes it possible to extend *VSL* measurements to large forested areas. Dendrometer measurements are taken at varying intervals on the stems, forks, and large branches either to the tip or to the last visible portion of the stem. The computer program then allows extrapolation or interpolation to as many different merchantable top diameters as are of interest. Small branches are ignored because they contain a small part of the total volume and considerable time is required to measure them. Dendrometry of the basal diameters of the primary branches and *VSL* values for the timber part of the tree should provide more acceptable allometric estimates for non-timber parts of the tree than d.b.h. and height data (Shinozaki, Yoda, Hozumi & Kira, 1964). For application to many stands and to large forested areas, the primary matrix is most economically constructed with *VSL* values for the timber part of the forest. The understory woody plants may be measured directly with tape and calipers to whatever dimensions are essential.

Ecosystem functions related to the primary matrix

The primary matrix is specific for a given stand primarily because of variations in the height, diameter, and taper of tree boles as related to age, stand density, rate of height growth, and size of the crowns. An increase in diameter at breast height can give misleading impressions of increases in bole volumes (Woessner 1973; Horn 1961; Jacobs 1954; Bickerstaff 1946). Thickness of the annual rings vary longitudinally in boles and branches in relation to tree dominance, size of crown, location and size of branches, stand density, genotype, and age (Farrar 1961; Reukema 1959; Duff & Nolan 1953; Larson 1956, 1963). Attempts to define stem form mathematically have been unprofitable (Grosenbaugh 1966; Larson 1963) except where trees of the same species were uniformly spaced in plantations (Bennett & Swindel 1972).

For a particular tree the primary matrix reflects all factors affecting the size and shape of the tree such as stand density, size and location of branches, age, and size of crown (Larson 1963). The primary matrix of stands reflects the interactions of all individuals and the differences in size and form of stems resulting from competition in relation to the specific location of each tree in the stand.

Separating *VSL* into an arithmetic progression of top diameters provides a way to examine growth from repeated measurements without concern for differences in stem taper. The formation of an annual sheath of wood and bark brings changes in the location of a given diameter and in distances between given diameters. These changes can vary with many growth conditions.

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Changes in the primary matrix are measures of change in organic matter distribution within and among trees.

Thus, the primary matrix for the timber component of the ecosystem provides a way to quantitatively measure and estimate responses of the ecosystem to silviculture. It is proposed that most responses to silviculture, such as water and nutrient flows, changes in understory herbaceous and woody plants, and accumulation of litter can be related by regression and similar techniques to changes in the primary matrix. Such relationships could provide a way to effectively and inexpensively link ecosystem production to applied silviculture.

These linkages have yet to be made quantitatively. In the extensive literature on ecosystem analyses, watershed yields, wildlife habitats, and silviculture, however, one can find numerous correlations of functions and responses with such measures as d.b.h., basal area, height, crown diameter, and volume of the trees. Elements of the primary matrix should provide more definitive correlations because the distribution of most of the accumulated organic matter in the ecosystem is expressed in the three primary units of measure. The primary matrix is an effective and relatively inexpensive way to describe forest stands and is a sensitive way to compare differences among trees and stands, to measure responses to silvicultural actions, and to estimate changes in the ecosystem in relation to timber production.

The primary matrix must be based on data from direct measurement of upper stem diameters and lengths. Estimates of volumes and surfaces from regressions are of value when only approximation of matrices are required. Sample trees and plots should be selected to reliably describe specific stands and ecosystems. Without these constraints on measurements and samplings, the effects of competition and interactions among primary producers may not be reflected in the primary matrix.

Bole surface related to timber potentials and ecosystem functions

Surface of the bole is the least investigated of the three primary units of measure. Until recently (Grosenbaugh 1963, 1971), tree bole surface was more difficult to measure than d.b.h. and height. With increased emphasis on intensive culture and with opportunities to use the primary matrix as a quantitative base for silviculture, increased emphasis should be given to studies of the surface of tree boles. Surface especially in combination with volume and length of tree segments is related to timber potentials and ecosystem functions.

Lexen (1943) illustrated the usefulness of bole surface in predictions of future forest growth. He concluded that surface is a simple growth expression of unusual utility.

Lescaffette (1951) proposed the use of surface of the main stem to assess annual increment and productivity. Because of the difficulty of measuring surface in standing trees, he estimated surface from the shape of assumed geometric solids for tree stems. Anuchin (1962, 1970) presents data supporting the assumption that the area of the surface of the bole of pine plantations in Russia may remain relatively constant during a period of 100 years. The data suggest that the lateral surface of stems in these plantations reached a constant at about 50 years of age for the higher sites and at later ages for lower sites. He found the surface area of boles to be proportional to the stocking of the stands.

Grosenbaugh (1954) pointed out that Clark (1906) originally conceived the International $\frac{1}{8}$-inch log rule as a function of volume, surface, and length of logs. As demonstrated by Grosenbaugh (1967), the inclusion of surface as a primary unit along with volume and length permits reliable estimates of a multitude of forest products from standing tree measurements.

Whittaker (1966) and Whittaker & Woodwell (1967) examined the surface area relations of woody plants in forest communities in the Southern Appalachians. Allometric relationships were demonstrated between surface areas of branches, leaves, and stems, and diameter at 1.37 m for trees and diameter at ground level for shrubs. Whittaker suggested that surface area of plants had important implications for respiration rates, energy exchange, and water and nutrient flows.

Bole surface changes in relation to stand development are not found in the literature except for the reports by Anuchin (1962, 1970). However, some idea of trends can be had by approximating bole surfaces from tables for growth and yield. If we assume a conic form for boles, which we know is incorrect, computations of lateral surface of boles from diameter and height data provide some figures that indicate trends with site index, species, and stand age. For example, for even-aged upland oak (*Quercus* spp.) forests in the eastern United States (Schnur 1937), the aggregate bole surface increases with site index and with dominant stand age up to 100 years (table 2). Bole surface increases rapidly in young stands and more slowly after 70 years of age. Differences between the two site index classes are larger for younger ages than for old stands.

TABLE 2. EXAMPLE OF BOLE SURFACES APPROXIMATED FROM GROWTH AND YIELD TABLES† BY SITE INDEX CLASSES AND AGE CLASSES FOR ALL STEMS LARGER THAN 1.5 cm AT D.B.H. AND FOR MERCHANTABLE BOLES

	site index 18.2‡		site index 21.3‡	
age class year	boles over 1.5 cm d.b.h.§	merchantable boles‖	boles over 1.5 cm d.b.h.§	merchantable boles‖
	m^2/ha	m^2/ha	m^2/ha	m^2/ha
10	1860	0	2160	0
20	3530	414	4100	877
30	4430	1970	4690	2560
40	4850	3250	5010	3600
50	5280	3990	5500	4350
60	5450	4450	5830	5050
70	5660	4920	6060	5470
80	6010	5410	6220	5750
90	6120	5620	6440	6010
100	6260	5780	6510	6110

† Approximated from tables 2, 16, 17 (Schnur 1937).

‡ Average height of dominant trees at age 50.

§ Approximate surface of entire boles, branches excluded, for trees with diameters above 1.5 cm at d.b.h (1.2 m).

‖ Approximate surface of boles with merchantable timber to a 10 cm top, branches excluded, for trees with diameters above 12.7 cm at d.b.h. (1.2 m).

From these data for oak forests (Schnur 1937) we can approximate total volumes, surfaces, and lengths for assumed primary matrices of oak stands by 10-year age classes (table 3). These figures suggest that mortality reduced the aggregate length of the timber boles after age 60 but that timber surfaces continued to increase. Figures for loblolly pine (*P. taeda* L.) (U.S.D.A. Pub. 50, 1929) (table 4) suggest that aggregate length, in this case for total heights, begins to decrease before surface decreases are evident. For the pine stands, surface and length seem to peak at culmination of mean annual increment, age 35–40. Apparently mortality in the pine stands after about age 30–40 is reducing length, surface, and mean annual increment.

For the pines at age 80, annual periodic growth for the recent decade is 1.4 m^3 with an annual decrease in surface of 6.9 m^2 and a loss in length of 38.4 m. Annual growth for the oaks for the same decade is 3.1 m^3 with an annual increase in surface of 49 m^2 and a loss in length of 3.2 m. Loblolly pine forests at these ages are rapidly invaded by hardwood species (Spurr & Barnes 1973) while the oak forests show a progressively smaller number of understory trees (Schnur 1937).

TABLE 3. TOTAL VALUES FOR PRIMARY MATRICES APPROXIMATED BY AGE CLASSES FOR UPLAND OAK STANDS, SITE INDEX 18.2 m,† FOR MERCHANTABLE BOLES TO A 10 cm TOP DIAMETER OUTSIDE BARK

age class	volume‡	surface§	length§
year	m^3/ha	m^2/ha	m/ha
20	11.9	414	1290
30	61.6	1970	4020
40	110.5	3250	5002
50	156.0	3990	5439
60	195.9	4450	5461
70	230.2	4920	5192
80	261.0	5410	5160
90	288.3	5620	4947
100	313.5	5780	4764

† Average height of dominant trees at age 50.
‡ Converted from table 2 (Schnur 1937). Volume includes bark.
§ Approximated from tables 2, 16, 17 (Schnur 1937). Surface includes bark.

TABLE 4. TOTAL VALUES FOR PRIMARY MATRICES APPROXIMATED BY AGE CLASSES FOR LOBLOLLY PINE STANDS, SITE INDEX 21.3 m,† FOR TOTAL BOLES LARGER THAN 10 cm DIAMETER OUTSIDE BARK AT D.B.H. (1.2 m)

age class	volume	surface	length
years	m^3/ha‡	m^2/ha§	m/ha§
20	132.9	4303	6995
30	234.4	6604	8588
40	314.9	7044	7733
50	363.8	6831	6637
60	398.8	6799	5925
70	419.8	6469	5258
80	433.8	6400	4874

† Average height of dominant trees at age 50.
‡ Converted from table 44 (U.S.D.A. Pub. 50, 1929). Volume includes bark.
§ Approximated from tables 35, 41, 42 (U.S.D.A. Pub. 50, 1929). Surface includes bark and length includes total heights.

The figures in these tables for surface area have an unknown amount of error because they were computed indirectly from an assumed conic shape of boles. The indicated trends are of value for guiding research to determine the true relation of surface to volume and height changes. The trends are taken as additional evidence that the biological potential for timber production can be expressed more usefully as a matrix of primary units than as single measures of volume and biomass. These matrices (table 1) or summaries of matrices (tables 2 and 3) can be sources of independent variables for ecological and silvicultural analyses. These analyses can provide basis for practical choices among alternative silvicultural actions and for estimating how much organic matter can be harvested as a crop in relation to other forest goods and services.

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