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PRODUCTIVITY ESTIMATION OF FOREST LANDS - D. F. Grigal

I would like to thank a number of people, including Willard Carmean, Grant Goltz, DeVon Nelson, and Don Prettyman, all of the USDA Forest Service, and John Hultgren of the USDA Soil Conservation Service, for helpful discussions concerning this topic. A review, "Forest Site Quality Evaluation in the United States", by Dr. Carmean, will soon appear in Advances in Agronomy, and I strongly recommend it for further development of some of the subjects I discuss here.

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I assume that the position of this paper, near the beginning of a conference on intensive forest management, is not fortuitous but intended. Measurement and prediction of forest land productivity is a first step in any intensive management program. This information is necessary to estimate growth, to decide upon harvesting times and techniques, to develop silvicultural prescriptions, and to conduct a host of other intensive forest management activities. The paper will be divided into three major parts: measurement of productivity, prediction of productivity, and modification of productivity.

I. Measurement of Productivity

Before forest productivity can be evaluated or predicted, the basis for the evaluation must be determined. In this paper, productivity will refer exclusively to timber production. Ideally, the units used to measure productivity should be closely related to units used to measure the ultimate product. To measure pulpwood productivity, volume, or better weight, should be used; for sawtimber, volume; and perhaps for pole products, some length-diameter measure.

In the United States, initial emphasis in forest management was on sawtimber. Standing timber was scaled by volume, and so productivity of a site should also have been measured that way. Accurate volume measurements, however, were not easy to make. Some other easily measured parameter, related to volume, was needed to measure site quality. Height soon came to be accepted as this parameter, and productivity on a volume basis was linked to height at an index age through yield tables (e.g. Buckman 1962). Height at the index age was termed site index. Many problems exist with the relationship between volume and height at an index age, and so the use of site index has been examined and re-examined in the literature (Vincent 1961, Sammi 1965, Cool 1965). However, it appears that site index will continue to be used to measure site productivity. It should be recognized, then, that almost all current methods of estimating productivity are based on estimating site index, not on estimating intrinsic volume productivity. Site index is the standard to which all other measures attempt to conform.

Recently, interest has grown in use of mass or weight to measure and estimate productivity (e.g. Blackmon and Ralston 1968). This interest comes from three directions. First, scaling of fiber products at the mill is increasingly being done on a weight basis. The logical measure of productivity for this material, therefore, should be weight. Secondly, and related to the first reason, is increased development of the concept of total utilization pioneered by Harold Young (1964) in Maine. Again, weight becomes a logical common denominator when comparing productivity of mature stands to "puckerbrush" stands or to stands of sycamore sprouts. The third reason for the interest in mass or weight to measure productivity is the development of that measure in plant ecology, especially when used to compare the productivity of different ecosystems. In this case, too, mass provides a common denominator by which productivity of chapparel, for example, can be compared to that of Douglas fir. Early work with this measure of productivity in ecology was done at the Cedar Creek Natural History Area in east-central Minnesota (Ovington, Heitkamp, and Lawrence 1963). Use of mass or weight as a measure of productivity is just developing, and so very little information related to it, such as yield tables, is available.

II. Prediction of Productivity

Assuming a consensus on the use of site index as the standard (only?) measure of productivity, we can begin to explore the problem of prediction of productivity for a site (or really, prediction of site index). Prediction of productivity, or of site quality, can be considered in two different ways. We can predict productivity for a point on the landscape, be it a fifth-acre plot or a single small stand. I will refer to this as a point estimate. Alternatively, we can predict productivity for an area delineated on a map, such as a compartment, district, or forest. I shall refer to this as an areal estimate.

A. Point estimate

1. Direct measure - The simplest and most straightforward method of predicting productivity, or of estimating site quality, is to directly determine the site index of the species of interest on the site of interest. Problems can arise with this method. First, if we have an ideal case where the trees are exactly 50 years old (or whatever the index age is), then the only error in site index determination would seem to be an error in determining tree height. With good instruments and technique, this measurement error can be greatly reduced. Other errors can occur, however. Site index curves are usually based on heights of dominant and codominant trees. If those trees have been removed by an earlier logging or thinning, then even a very careful measurement of the remaining trees will not indicate the true potential height of the stand. Other disturbances or events during the history of the stand, such as insect injury or frost damage, may also invalidate use of the present trees as good indicators of site index.

   If the trees are not exactly 50 years old, other problems occur. First, if site index curves are based on age of establishment, an estimate usually must be made of the time it took the tree to reach breast height. A large error in this estimate can result in an error in the site index estimate. Such an error is likely to occur if the young stand was subject to severe competition, for example. A more serious error can occur when older, or harmonic, site index curves are used. These curves assumed that rates of height growth of trees were approximately parallel over a wide range of site classes. This is not true. Work has shown that rates of height growth on poor sites for example, may be very different from those on good sites; that is, the growth curves are polymorphic (Carmean 1970). Trees on a poor site may have fairly rapid early height growth, but as the potential of the site is reached, height growth may slow. Trees on a good site may continue rapid height growth over a much longer time. Other possibilities are possible, but the point is that site index, and thus productivity, may be incorrectly estimated if the trees which are measured have a pattern of growth that does not conform to that recorded on the site index curve.

   Density may also be related to height growth in some tree species, ranging from oaks (Gaiser and Merz 1951) to ponderosa pine (Lynch 1958). If corrections for density are not made, estimates of site index may be in error. Genetic differences, too, can affect height growth of trees. The most obvious example of this is in aspen, where clones may have measurably different heights at the same age on the same site (Zahner and Crawford 1965).

   Site index determination may also be affected by other factors which I have not mentioned, such as tree height variation and stand origin differences. I have devoted so much space to this topic because a major assumption was that mature trees of the species of interest were on the site. As I discuss other methods of predicting productivity, keep in mind the potential errors in this simple, idealized case.

2. Growth-intercept - If immature rather than mature trees of the species of interest occupy the site, then the growth-intercept method can be used to estimate site quality (Wakeley and Marrero 1958). In this method, the five-year height growth above breast height is related to site quality. Easily distinguishable annual whorls are usually necessary, although modifications of this method have used average annual height growth (Stoate and Crossin 1959). Growth-intercept has been related to later height (Ferree, Shearer, and Stone 1958). Alban (1972) found that in red pine in Minnesota, the five years of growth above eight feet was closely related to height at age 50 (site index).

   If the species of interest does not occur on the site, or if its growth has been seriously affected by disturbance, other methods are available to predict productivity.

3. Inter-species correlation - A straightforward method to predict productivity for a species which is absent from a site is to use the relationship between the site index of that species and the site index of another species which does occur on the site. Relationships have been developed for some species combinations (e.g. Carmean and Vasilevsky 1971). However, all errors that have been discussed previously in measuring site index are valid here, but now compounded by the addition of another species. Errors can also occur because both species may, on the average, have related rates of height growth, but at any particular site such rates may vary greatly.

4. Soil-site studies - If no species of interest is on the site, and no inter-species correlations are available, a potential method of productivity prediction is a soil-site relationship. This technique is reviewed in some detail by Carmean (1975). Extensive work has shown that site index can be reasonably predicted by characteristics of the soil and site, including such features as thickness of the surface horizon and percent slope. Equations are developed which relate these features to the site index of a species of interest. The relationship, however, must have been developed for the species and in the geographic area. Even if these criteria are met, the method still has pitfalls. The relationship is only good for the population of stands which were used in its development. If a stand does not belong to that population, then use of the relationship will surely lead to errors in prediction. For example, if the relationship were developed on soils formed in till, and the stand of interest is on outwash sands, then the population is probably different. Geographic location, perhaps as it affects climate, alters the relationship. Most disturbing of all, however, is that in some cases the relationships seem to break down even after the above criteria have apparently been satisfied (Broadfoot 1969). The key word here is apparently. For some reason, all criteria have

not been satisfied. Unfortunately, it may not be possible to determine, or even be aware of, the problem.

5. Vegetative site index - Another method of predicting productivity at a point is a vegetative site index. In this method, relationships have been developed between (usually) understory species and tree site index. Some measure of these species, such as frequency, is plugged into an appropriate equation, and the site index is estimated. Some success has been reported with this method (MacLean and Bolsinger 1973, Hodgkins 1970). Again if no relationship has been developed, no estimate can be made.

6. Soil classification - Finally, the last method for a point estimate of productivity is to excavate a soil profile, describe it, and determine the soil taxonomic unit to which it belongs (most often this unit is a soil series). For most such units, means and ranges of site index for various species have been determined and are published in a "Soil Survey Interpretation". This method of site evaluation is lengthy, in that the soil profile must be exposed; and some expertise in soil science is necessary to describe and classify the soil. Finally, there is some question about the accuracy of the prediction of productivity based on a soil taxonomic unit. I will discuss that problem in more detail later.

B. Areal estimates

For forest management, site productivity estimation must be concerned with assessing the productivity of units of land, not simply points on the landscape. Only if point estimates are related to units of land can the results be readily used in management plans. For critical areas where very intensive management is necessary, point estimation is useful. Point estimates are also useful in interpreting maps. But maps are essential. As Daubenmire (1973) stated, maps provide information on (a) the kinds of landscape units, (b) the amount of each, and (c) their pattern of distribution. All this information is necessary for effective land management.

1. Maps: basic information - Use of maps is closely tied to many phases of forestry, and perhaps a discussion of maps *per se* is not necessary. On the other hand, many serious misinterpretations about maps, and particularly soil maps, are based on misunderstandings concerning their construction and especially concerning map scales.

   Intensive or ideal management at the present time appears to be aimed toward stands about 10 acres in size. An appropriate map scale to display information on units of this size is about 1:24,000 or larger. This is the scale of the U.S. Geological Survey 7-1/2 minute topographic quads. Minimum delineations on maps smaller than that scale must be larger than 10 acres. To be specific, in Minnesota at the present time we have a state soil map published at a scale of about 1:2,000,000 (Arneman 1963).

Units delineated on this map are only adequate for planning at a very high level. The Department of Soil Science at the University of Minnesota is currently in the process of producing a series of maps of the State at a scale of 1:250,000. When the state map is compared to these more detailed maps, the latter maps appear to be extremely detailed. However, at the scale of 1:250,000, the minimum size soil mapping unit that can be meaningfully delineated is about 640 acres. Thus, this map should only be used at a level of abstraction that recognizes this restriction. Decisions or interpretations should be made which are consistent with the scale of mapping (not the scale of reproduction, which may increase or decrease the mapped scale).

The second point about maps is that units delineated on them are referred to as mapping units, as opposed to taxonomic units. In forestry, every tree occurring in an area mapped as jack pine cover type is not expected to be jack pine. Although both the mapping unit and the taxonomic unit have the same name, it would not be surprising to find some red pine, or aspen, or birch within a particular delineation. By the same token, a delineation in the Menahga soil mapping unit is not exclusively occuppied by members of the Menahga soils series (the taxonomic unit). Depending on the landscape, a Menahga mapping unit may be more or less "pure" in terms of Menahga soil series. This is very important in interpretations of soil maps. If a unit only contains 60% Menahga series, then interpretations of this unit cannot be based on the assumption that it is wholly composed of that series. The degree of error in that type of interpretation depends on what occurs on the other 40% of the mapping unit.

2. Site maps - A number of features of the forested landscape have been used to determine mapping units which can be related to forest productivity. I will arbitrarily consider delineations of site by three broad techniques; mapping by physiography, by vegetation, and by soils. There is overlap, however, in all of these techniques.

   a. Physiography - Use of physiography as a basis for mapping has been practiced most extensively on large, relatively inaccessible land areas. These methods have been most widely used in Austrailia and Canada. Mapping usually depends heavily on aerial photography, with a minimum of field checking. One of the most well-known methods of mapping with a physiographic basis was developed by Hills and his coworkers in Ontario, Canada. In Hills' method, physiography provides a stable framework within which soils and vegetation are considered. The relief of a landscape, the pore distribution pattern (primarily soil texture and structure), and the potential chemical elements in the soil are assumed to affect the ecoclimate and the soil moisture and nutrient regimes. These factors, in turn, influence both the composition and the productivity of the vegetation.

Actual mapping by Hills' method relies heavily on landform and vegetation composition. The resulting maps have proved to be valuable both for estimating productivity and as a basis for planning for other uses of the land (Burger 1972). The criticisms of this technique center on its lack of quantification, and consider the method to be too much art and too little science. Apparently, the best way to learn to use the method is to work with Hills and his colleagues.

b. Vegetation - Site maps or classifications based on vegetation range from those using only overstory to those using only understory to those using a combination of the two. One of the earliest proponents of use of vegetation for forest site classification was Cajander, from Finland. He developed a system of classification that was heavily weighted by the understory (Cajander 1926). Yield tables and silvicultural prescriptions were developed for each of the recognized types. In the view of some, application of the method required the Finnish foresters' appreciation and knowledge of plant ecology. Others felt that the success of the method lay in the relative simplicity of Finnish vegetation, with few major species. The method was, therefore, both easily applied and provided meaningful units. Extrapolation of the method outside Finland has generally not been successful, perhaps because of more complex vegetation elsewhere.

In the United States, the strongest proponent of a vegetation approach to site classification is probably Daubenmire, who feels that he has developed a workable system of "habitat types" for the western Intermountain area. Habitat types can be considered to support, or to be capable of supporting, the same kind of climax vegetation. The type is named by that climax (Daubenmire and Daubenmire 1968). His system uses both overstory and understory vegetation, and keys have been constructed for its use. Habitat types have been found to be related to soils. Daubenmire (1961) has also related the types to site productivity and disease infestation. Most detractors of the system feel that because it took nearly a lifetime to set up and because Daubenmire dealt with uniquely minimally disturbed stands, the system is difficult to use and even more difficult to extrapolate elsewhere.

c. Soils - Mapping soil bodies as they occur on the landscape is well-established in the United States, and is one of the primary tasks of the National Cooperative Soil Survey. Such mapping has been carried out on agricultural lands since the turn of the century, and more recently emphasis is being placed on mapping forested lands. A good soil map, at an appropriate scale, is very useful in land management. Decisions concerning road location, sources of borrow, potential recreation sites (or sites to be avoided), areas with erosion hazard, areas which have limitations in terms of heavy equipment use, and so on, can be identified with the aid of such a map. But what about silviculturally significant areas? Can reproductive success be determined? Can productivity be evaluated? The answers to all these and other questions concerning the utility of soil maps is yes and no and maybe.

For intensive forest management prediction of productivity in classes of 10 feet of site index, or in other words, $\pm$ 5 feet, is desirable. Can a soil map provide that resolution? The answer to this question lies in the kinds of units delineated on the map, and in the interpretations developed for those units. In a standard soil survey, mapping units are most often defined on the basis of a predominant soil taxonomic unit, usually the soil series. Interpretations for productivity are developed for the taxonomic unit and applied wherever that unit occurs. Problems can occur in the development and application of these interpretations.

First, for some reason, and usually because of lack of time and/or funds, only a limited number of examples of a taxonomic unit may have been sampled to determine its productivity. Therefore, interpretations, including those concerned with productivity, are done from a small data base. Thus, errors can occur. A second problem may occur when a large number of examples of a taxonomic unit have been sampled to determine productivity. In this case, the range of site index over a given unit is often very large, or the mean site index for a number of different units may be the same. Estimates of productivity based on these data are uncertain. Large variations in site index for a given taxonomic unit can occur for at least two reasons. First, a unit may occur over a fairly wide geographic range and so interpretations are developed over this range. If climatic factors, for example, strongly affect productivity, then climate and thus productivity are likely to vary from one end of the geographic range to the other. Secondly, every taxonomic unit is defined with a range of characteristics within which it can occur. Some of these characteristics may be important for tree growth, and a wide range of them can result in a wide range in productivity. For example, a relatively small change in depth to water table may not affect the taxonomic position of a soil, but may profoundly affect tree growth.

Even if interpretations of each taxonomic unit are accurate and precise, interpretations must be translated to areas of land via mapping units. If a taxonomic unit only comprises 60% of a mapping unit, what is the productivity of the other 40%? The problem is particularly vexing if the productivity of the inclusions is very different from that of the dominant unit.

If soil surveys have all those problems, what good are they? Very good. Ask the people who made them, or those who use them. As I stated earlier, they contain a wealth of information concerning potential road location, trafficability, erosion hazard, recreation uses, and so forth. They also provide a framework for the assessment of productivity. On a broad basis, such as the State of Minnesota or the Eastern Region of the USDA Forest Service, interpretations based on conventional taxonomic units are useful for planning purposes. When smaller units of land such as a particular National Forest are considered, then additional interpretative data, using more information than simply a soil map, are probably necessary. The basic soil map, however, does provide the data base for a number of uses.

What kinds of data are needed to convert a soil map to a productivity map? Each of the National Forests in Minnesota, the Chippewa and Superior, have approached this problem somewhat differently. On the Chippewa National Forest, the soil scientist has found that productivity on the same soil mapping unit changes across the forest. He has related this to factors associated with a presumed age sequence of glacial deposits, with soils formed in the youngest deposits being the most productive. Thus, using the soil map and information concerning the glacial history of the area, he can interpret the productivity of the mapping units.

In the Superior National Forest, the emphasis has been on vegetation as an additional indicator of productivity, both in terms of vegetation composition and quantity. The result of using soils, vegetation, and in some cases landform is units which are uniform in productivity. In some cases these units closely correspond to a soil mapping unit, in other cases they may subdivide a mapping unit and in still other cases they may span two or more mapping units.

I would like to make the point that these two approaches are not diametrically opposed to one another. The key to both approaches lies in gathering more information than that strictly related to soil in order to develop units that can be more confidently interpreted or evaluated.

What does the future hold in terms of evaluating productivity on the landscape? There is no doubt that a blending of soil, vegetation, and geological data is necessary in order to get the best handle on the productivity of a forest. Most publications dealing with the subject of productivity evaluation urge that this be done, but most of them are at a loss to detail exactly how the blending is to be accomplished. I doubt whether the simple expedient of assembling a soil scientist, a geologist, and a plant ecologist and putting them to work together will accomplish what is needed. I find a consensus of opinion, at least in my own mind, that the soil survey will continue to be one of the backbones of land use management and decisions. However, determination of mapping units should be made in consultation of potential users of the map; and be made before mapping begins. It is often said that a good soil map should be produced and interpretations developed later. That is not quite true. It is better to develop mapping units with cognizance of interpretations. For example, if soils are found to vary in productivity according to factors associated with age of glacial deposits, recognition of this before a soil survey begins would be extremely important. It would be simple to separate mapping units during the survey on the basis of properties associated with age of deposit, and to develop separate interpretations for each unit. Those factors which affect productivity in a given geographic area must be determined and used in developing mapping units. It is here that soil-site studies have a role. If they are well done, they will identify factors which are important to tree growth within an area, and which should be recognized when mapping units are established.

Another point I would like to make is that if we are talking about dealing with 10 acre land units, or units even smaller in some cases, then it is not realistic to attempt to do all site or productivity classification directly from aerial photos in the office. Each unit should be visited. The units are visited when a timber sale is prepared, but it is as important to visit them and determine their properties before a management decision, such as whether to put the timber up for sale or not, is made. Systems of site classification that use understory vegetation, then, if they lead to units with similar productivities and silvicultural prescriptions, should be carefully considered. Such systems, however, should be quantitative so that they can be applied uniformly by a variety of personnel. I personally believe that a technique such as a mathematical discrimination function (Grigal and Ohmann 1975) would be very useful for such a system.

III. Modifications of Productivity

Now that I have developed the concept of prediction of productivity, I will briefly discuss methods of increasing or modifying productivity.

A. Present practices

Surely the first methods to consider for modifying productivity are present practices. In view of the probable continuing scarcity of energy, practices which have low energy costs should be considered most closely. I will mention their general possibilities.

The first method of increasing productivity is to simply match species to site. In this way, the productivity of each acre of land is maximized. On one Ranger District in the Nicolet National Forest in Wisconsin, Stevens and Wertz (1971) predicted a 60% increase in sawtimber yield by simply matching tree species to the soils on which they were most productive. Even when multiple use considerations were included, increases in productivity over the forest were still in the 20% to 40% range.

The second method of modifying productivity is simply more intensive silviculture. Thinning studies all over the world have shown productivity increases. For example, in a recent study in Ponderosa pine, Youngberg (1975) found that thinning increased growth over a five-year period more than did fertilization. Better stocking, immediate regeneration, release from competing vegetation, and similar techniques will result in substantially increased yields on our present acres.

The last but certainly not the least of the present methods I recognize to increase productivity is better utilization of all the fiber that is produced on an acre, or at least utilization of all whose removal does not seriously degrade the site. I confess that I am disturbed by the degree of whole tree utilization where small twigs, buds, and leaves are removed. Net cost of such a system because of site degradation may be greater than the return from that degree of utilization. Chappell and Beltz (1973) did find that 25% of the gross volume exclusive of roots remained in southern pine forests after clearcutting. Another facet of increased utilization is better use of present non-commercial species, especially hardwoods. Einspahr and Benson (1970) predict that use of hardwoods will quadruple by the end of the century, and account for 40% of total domestic pulpwood production. This utilization will increase at a low cost the amount of fiber produced by our forests.

B. New practices

I am going to spend very little time on the subject of new practices to increase productivity. The two practices I would like to highlight for increasing inherent productivity of a site are drainage and fertilization.

The Finns have extensively used drainage of wetlands, and especially peatlands, to increase production in a landscape similar to that of the Lake States. They have found that the increased productivity of their wet sites is of enough value to offset drainage costs. By the beginning of the 1970's, a total area of 8,640,000 acres of land had been drained, resulting in an estimated annual increase in growth of about 30 ft^3/ac (Heikurainen 1972). Whether a favorable cost/benefit ratio will continue in light of increased energy costs is a question which must be considered.

Fertilization is receiving more and more attention as a technique to increase productivity. It is now operational in the South and the West, and a number of research studies are being carried out in Northeastern United States and Canada, in areas similar to the Lake States (Northeastern Forest Experiment Station 1973). Experiment evidence has shown rather conclusively that if trees are fertilized, they grow faster. At the present time, most interest in fertilization seems to be centered among researchers and those in higher levels of administration -- people whose job it is to look ahead. Certainly, adoption of fertilization as a widespread forest management practice requires a careful analysis of cost vs. benefit. Such an analysis is often lacking in present fertilization studies.

In conclusion, I believe that we are getting ever closer to a handle on estimating or evaluating site productivity. With that information, and with techniques we already have in our tool box, productivity of our forests can be very measurably increased.

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