uneven-aged prescriptions, presented to a silvicultural shortcourse.

LESSONS LEARNED

All of the case applications revealed some common truths and insights. Comprehension of complex land management problems was rapid by anyone interested in the problem. Substantive discussions could be held within 2 hours of a cold start, including time for a brief technical tutorial. With the spreadsheet visibility of this simple technique, much of the technical barrier to understanding how analysis works is removed. The proportion of time and attention devoted to assumptions, data quality, problem formulation, concepts, and analysis is greatly increased. Finally, the heretofore practical difficulty of quickly changing biophysical, social, and economic technical coefficients in linear programming models is eliminated. Beyond these rather obvious benefits, some amazing and unexpected things happened in the interaction of the students and policy makers as they communally used the method to work on a problem.

1. Almost without saying, participants learn that they control the analytical system. It is not just a "black box." Changes in the spreadsheet data and the constraint control file immediately result in intuitively satisfying changes in the results printed in the report file. Users see how they and others can control the solution by hardwiring particular choices, changing data, and adjusting output policy.
2. Users build trust in professional analysts and each other. Work is open, data can be reviewed, and complex outputs are not produced in windowless back rooms. The role of analyst is seen and appreciated for providing important decision support information to policy makers.
3. Real time policy analysis is possible. With suitable preparation of the base models, groups of stakeholders can meet, and within the time frame of an afternoon workshop, review proposals, conduct sensitivity analysis, modify alternatives, and learn the range of feasible choices. Copies of spreadsheet and other files can be taken home to test new assumptions, create new alternatives, and bring new ideas and propositions back to future meetings.
4. Participants can better see each others' viewpoint. Each participant can formulate a problem from his or her own viewpoint. By sharing results and data files they can see how others with different values formulate the same problem. As participants begin to understand each other better, they move to identifying shared interests and looking for innovative ways to achieve them.

GETTING STARTED

To run this system on problems ranging up to 2000+ columns and 500+ rows, we recommend at least a 80286 class PC with a 80287 coprocessor, equipped with a hard disk and 2 megabytes of RAM. A higher speed 30386/87 system is much better at this. A printer for hard copy reports and a color graphic monitor is helpful. Portability of equipment is important if one wants to travel, do demonstrations, teach classes, or provide real time support for a discussion or negotiation workshop. A projection pallet to enlarge the computer screen image through an overhead projector is especially useful for group use and demonstrations. For software you will need a copy of a spreadsheet (LOTUS or EXCEL) plus hyper-LINDO (Schrage 1987). In addition to the EQUATION and REPORT programs (Schurr and Davis 1988), other commercial software, data base management systems, and custom programs can be adapted to implement the concepts of this technique. Copies of files and text for many of the test applications described in this paper can be obtained from the authors. ☐

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Assessment of Growing Stock in Uneven-Aged Stands

James N. Long and Theodore W. Daniel

The assessment and control of growing stock is a critical and difficult part of effective stand management. Recent research on the basic principles of stand development, especially the relations between mean tree size and population density, has contributed greatly to the development of practical tools for sound density management (Drew and Flewelling 1979, Gringrich 1967, Long and Smith 1984, Wilson 1979). While most of this research has concentrated on even-aged stands, it can also be used to assess growing stock in uneven-aged stands.

Density management of uneven-aged stands is inherently more complicated than that of even-aged stands. In addition to controlling the overall level of growing stock, the silviculturist must also decide the maximum tree size to retain and how to distribute growing stock among the various diameter classes. Most commonly, the residual level of growing stock has been based on stand basal area, which is apportioned among the diameter classes using an appropriate Q-factor (Leak and Gottsacker 1985). There are two major limitations to this approach: The excessive number of small trees dictated by a strict application of commonly used Q-factors; and the difficulty of interpreting, in terms of growing stock, basal area across a range of diameters.

We review how an index of stand density, based on size-density relations, is used to assess growing stock in even-aged stands and suggest how this basic approach can be applied to regulate growing stock in uneven-aged stands. An example from southwestern ponderosa pine illustrates the proposed method and compares it with the traditional basal area and Q-factor approach.

BACKGROUND

A successful density management regime must translate general management objectives into specific stand structure attributes, such as appropriate tree sizes and levels of growing stock. The formation of density man-

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agement prescriptions ultimately depends on the silviculturist's ability to assess levels of growing stock. Considerable basic and applied work, particularly over the last two decades, has provided substantial information on the assessment and control of growing stock in even-aged stands.

The relation between mean size and density of individuals in even-aged populations experiencing self-thinning is surprisingly predictable and is the basis of a number of stand density indexes (Ando 1968, Drew and Flewelling 1977, Long and Smith 1984, Reineke 1933). Indexes based on size-density relations are independent of site quality and stand age (Curtis 1970, Daniel et al. 1979, Wilson 1979) and make it possible to compare levels of growing stock independent of these factors. Thus a level of growing stock, represented by a given mean size and stand density, that is deemed ideal in a particular management context can be projected to an earlier or later stage in the rotation of an even-aged stand.

Reineke's (1933) Stand Density Index (SDI) is probably the most commonly used size-density index. SDI is especially useful to silviculturists because it is easily estimated and applied (Curtis 1982, Daniel et al. 1979, Long 1985). Conceptually, the SDI of an even-aged stand is the number of trees per acre (*TPA*) based on a quadratic mean diameter (*Dq*) of 10 inches. Given the actual *TPA* and *Dq*, *SDI* can be calculated:

$$SDI = TPA(Dq/10)^{1.6} \qquad (1)$$

Given *SDI* and either of the stand parameters, the third parameter can be calculated:

$$TPA = SDI/(Dq/10)^{1.6} \qquad (2)$$

$$Dq = 10(SDI/TPA)^{0.625} \qquad (3)$$

While the calculation of *SDI* is independent of species, it is useful to express *SDI* as a percent of the maximum *SDI* for the species (*%SDI*) to facilitate the development of density management prescriptions. For example, Long (1985) suggests that some key values of *%SDI* are represented by 25% (onset of competition), 35% (lower limit of full site occupancy), and 60% (lower limit of self-thinning). *%SDI* has also been related to average live crown ratio (Long 1985), canopy closure (Smith and Long 1987), and total stand sapwood and leaf area (Long and Dean 1986).

These sorts of generalities are useful in determining target levels for growing stock. The stand is allowed to grow to the target upper limit and is thinned down to the target lower limit. In principle this process is repeated for an indefinite number of thinning cycles; in practice the process is modified to accommodate other management objectives such as minimum merchantable tree size and minimum volume removal constraints (Long 1985, McCarter and Long 1986).

Those who use SDI, or any index of stand density, as an estimate of growing stock must assume that the index is proportional to site utilization. Since the contribution of individual stand components to both total SDI and, presumably, total site utilization, is additive (Stage 1968), SDI can be used to assess control growing stock in uneven-aged stands. We suggest that the most general expression of SDI is:

$$SDI = \Sigma(DBH_i/10)^{1.6} \qquad (4)$$

where DBH_i is the diameter of the *i*th tree in the stand.

The calculation of *SDI* for an even-aged stand [Equation (1)] is simplified by the fact that the *SDI* of the tree of average basal area (*Dq*) multiplied by *TPA* is nearly equal to the summed *SDIs* of each tree when the diameter distribution of the stand is approximately normal. This can be demonstrated by generating a normal diameter distribution and comparing the *SDI* calculated with *Dq* and *TPA* [Equation (1)] with the *SDI* calculated as the sum of individual tree *SDIs* [Equation (4)]. It is less accurate to calculate component *SDIs* for diameter classes rather than individual trees, but this bias is probably of little practical concern when the diameter classes are not excessively broad.

For uneven-aged stands, there are two reasons why it is necessary to estimate *SDI* by summation of individual tree or diameter class *SDIs* [Equation (4)]. The first is that Equation (1) is inappropriate for the skewed diameter distributions typical of uneven-aged stands. The second is that it is not just the total stand level that is important in uneven-aged stands but also the way that this growing stock is partitioned among the various size classes.

AN EXAMPLE BASED ON SOUTHWESTERN PONDEROSA PINE

Schubert's (1974) recommendations concerning stocking and stand structure for uneven-aged southwestern ponderosa pine will be used to illustrate various points concerning levels of growing stock and its distribution among diameter classes. For various levels of residual basal area, Schubert used a *Q* of 1.22 (1 in. diameter classes) to apportion growing stock between diameter classes. Table 1, based on 2 in. diameter classes and a *Q* of 1.5, represents Schubert's recommended stand table for a residual stocking level of 80 ft^2/ac (note that a *Q* of 1.22 for 1 in. diameter classes is nearly equivalent to a *Q* of 1.5 for 2 in. diameter classes). We divided the data into four diameter groups roughly equivalent to the progression of a tree through the series of cutting cycles; a fifth group would be regenerated when mature crop trees are harvested. This representation assumes that the number of trees in each diameter group will be reduced enough to maintain the desired structure and stocking.

It is apparent that growing stock, as estimated by *SDI*, is not apportioned equally among the groups (Table 1). It is also clear that a *Q*-factor of 1.5 results in the concentration of growing stock into the smaller diameter classes. The higher the *Q*-factor, the greater the concentration of growing stock in the smaller diameter classes. Table 2 illustrates the stand structure when a *Q*-factor of 2 is used to distribute the same basal area (i.e., 80 ft^2/ac) among the diameter classes. In this case, nearly 88% of the trees and 55% of the *SDI* are in the smallest diameter

Table 1. Trees per acre and *SDI*, by 2 in. diameter classes; total basal area is 80 ft^2/ac and the Q-factor is 1.5 [after Schuburt (1974)].

Dbh class	By class		By group	
(in.)	*TPA*	*SDI*	*BA*	*SDI*
2	92.5	7.0	15.5	41.7
4	61.6	14.2		
6	41.1	18.2		
8	27.4	19.2	29.1	54.2
10	18.3	18.3		
12	12.2	16.3		
14	8.1	13.9	22.6	34.8
16	5.4	11.5		
18	3.6	9.2		
20	2.4	7.3	12.8	17.3
22	1.6	5.7		
24	1.1	4.2		
Totals	275	145	80	148

Table 2. Trees per acre and *SDI*, by 2 in. diameter classes; total basal area is 80 ft²/ac and the *Q*-factor is 2.0.

Dbh class (in.)	By class		By group	
	TPA	*SDI*	*BA*	*SDI*
2	308.1	23.5		
4	154.0	35.6	35.5	98.7
6	77.0	34.0		
8	38.5	26.9		
10	19.2	19.2	31.5	59.6
12	9.6	12.9		
14	4.8	8.2		
16	2.4	5.1	10.6	16.5
18	1.2	3.1		
20	0.6	1.8		
22	0.3	1.1	2.6	3.5
24	0.2	0.8		
Totals	616	172	80	178

group. This shift was associated with a 20% increase in total *SDI* and the fact that trees in the two lower diameter groups accounted for nearly 90% of the *SDI*, even though total basal area remains the same. This interdependence between basal area, *Q*-factor and level of site utilization, as indicated by *SDI*, is often overlooked. This interdependence probably reflects the financial inefficiency of uneven-aged management systems based on high *Q*-factor diameter distributions (Bare and Opalach 1988).

An alternative is to apportion growing stock among the various diameter classes or groups on the basis of *SDI*. Assume, for example, that the level of growing stock represented by the *SDI* in Table 1 (i.e., about 150) is appropriate, and that most of this *SDI* is equally allocated among each diameter class 8" and greater. For this example, we assume that these diameter classes are merchantable. *SDI* is allocated to the submerchantable diameter classes in proportion to diameter (Table 3). This particular distribution illustrates that while the number of trees in the submerchantable diameter classes provide insurance against loss and the opportunity for selection of crop trees, this excess need not provide the same degree of site occupancy as the diameter classes that are merchantable. Note that the smallest diameter group represents only 15% of the total growing stock, as represented by *SDI*, but contains over 50% of the *TPA* (Table 3).

As in even-aged systems, an appropriate residual level of growing stock for an uneven-aged system must reflect specific management objectives. Inevitably, this decision involves a compromise between full site occupancy (and maximum stand growth) and rapid individual tree growth (Long 1985). The maximum *SDI* for southwestern ponderosa pine is approximately 450, and the levels of growing stock recommended by Schubert (1974) for the beginning and end of a cutting cycle correspond to approximately 33% and 52%, respectively. These are very similar to the upper and lower limits to growing stock that Long (1985) used in a "high volume" density management regime for an even-aged stand. It is mistakenly assumed that levels of growing stock approaching full site occupancy are invariably desirable in managing uneven-aged stands. As uneven-aged management systems are increasingly used to accomplish a variety of nontimber objectives relating to recreation, wildlife, and visual resources, it may be appropriate for residual levels of growing stock to be substantially below full site occupancy.

Table 3. Trees per acre and *SDI*, by 2 in. diameter classes; total *SDI* is 149 (approximately that of the stand represented in Table 1 and 33% of maximum *SDI*).

Dbh class (in.)	By class		By group	
	TPA	*SDI*	*BA*	*SDI*
2	39.4	3.0		
4	30.3	7.0	8.4	22.1
6	24.9	11.0		
8	20.0	14.0		
10	14.0	14.0	22.9	42.4
12	10.5	14.0		
14	8.2	14.0		
16	6.6	14.0	27.6	42.2
18	5.5	14.0		
20	4.6	14.0		
22	4.0	14.0	31.4	42.1
24	3.4	14.0		
Totals	171	147	90	149

Assume, for the purposes of illustration, that the level and distribution of growing stock represented in Table 3 is appropriate for a particular set of management objectives. Such a stand structure would be only the start of the development of a silvicultural system. Some of the practical considerations to consider, particularly those related to the use of *SDI* in regulating growing stock, are discussed below. Leak and Gottsacker (1985) discuss several practical suggestions concerning implementation of silvicultural prescriptions in uneven-aged stands.

Basal area, by diameter class, must be estimated to determine existing structure and in order to mark for desired structure. Plotless cruising, with prism or relaskop, greatly facilitates collection of the necessary data (Daniel et al. 1979, p. 267). Achieving the desired stocking levels is undoubtedly the most difficult part of uneven-aged management (Leak and Gottsacker 1985). A theoretically sound distribution of growing stock is worth little if it is not reflected in actual stocking.

In implementing any uneven-aged system, regeneration must be successful, and levels of growing stock across the entire range of diameter classes must be controlled during each cutting cycle. Both of these critical elements are often taken for granted. Unfortunately, some managers mistakenly assume that the necessity for regeneration and early stand tending, which are so obvious in even-aged management, can, in the short term, be ignored in uneven-aged management. While uneven-aged systems provide a great deal of flexibility and opportunity for management, they generally require more, not less, attention to silvicultural detail to be successful. ☐

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Mineral Deficiency Symptoms in Pacific Northwest Conifers

Richard B. Walker and Stanley P. Gessel[1]

Forest trees growing on good sites are usually well supplied with mineral nutrients through normal weathering, mineralization, and mineral cycling in the forest. But for more than a century, the occurrence of mineral deficiencies, and the improvement of growth through mineral fertilization, have been reported from forests throughout the world. Mineral nutrient deficiencies lessen the general health and well being of trees and reduce their growth rates. As a result, the trees may become more susceptible to disease and other stresses. Such deficiencies may occur because the sites are inherently low in one or more elements, or because rates of supply are too low. Deficiencies may also be brought on by accelerated removal or losses of elements from repeated forest harvests, burning, erosion or use of the land in the past for agriculture (Isaac and Hopkins 1937, Rennie 1955, Kraemer and Hermann 1979, Little and Klock 1985).

In order to correct deficiencies, we need to be able to identify the element or elements involved. A knowledge of visual deficiency symptoms can be very useful in such identification, although leaf analyses are often used to verify a visual diagnosis, or to detect invisible deficiencies. Of course, growth may be slowed by such incipient deficiency (sometimes called "hidden hunger") before visual symptoms appear.

Any diagnosis of abnormalities needs to consider various possible causes, including mineral deficiency. Fungal or viral diseases, insect attacks, frost, heat, drought, excess water, salinity or salt spray, misapplied pesticides, air pollutants, or even normal senescence may produce symptoms which resemble those of mineral deficiencies. Good illustrated considerations of such possible confounding influences are included in Wallace (1961), Malhotra and Blauel (1980), and Sinclair et al. (1987).

THE NATURE OF DEFICIENCY SYMPTOMS

Fortunately, deficiency symptoms are similar in agricultural and in forest species, both broad-leafed and coniferous, so a general description can be given of their nature and patterns.

One or more of the features described here are involved in most displays of deficiency:

1. *Chlorosis* is the partial-to-complete loss of chlorophyll, making the leaves pale green, yellowish-green, or completely yellow. The yellow color is due to the carotinoid pigments, which in normal leaves are masked by the chlorophyll.
2. *Necrosis* refers to dying of tissue, which then takes on a tan or brownish color. Tips or margins only may be affected, or necrotic spots may appear on the leaves. When extreme, the entire leaf becomes necrotic and is usually soon shed from the plant. Periodic observations of the same needles may show a progression of necrosis from the tips toward the bases.
3. *Distortion or curling* of new leaves is caused by deficiencies that affect the bud or meristem, especially involving calcium or boron. Sometimes a number of such distorted leaves are clustered together at the tip of the stem, forming a rosette.
4. *Reddish pigments.* Some plant species form reddish or purplish pigments in their leaves and stems. These anthocyanins are often more abundant in deficient than in healthy plants. They are usually reddish in the case of nitrogen or sulfur deficiency, but purplish in phosphorus deficiency. Among our northwestern conifers, western red cedar (*Thuja plicata*) forms anthocyanins readily, which is useful in diagnoses for this species. Sitka spruce (*Picea sitchensis*) forms only small amounts of these reddish pigments, while Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) form almost none. This places a distinct limit on the specificity of symptoms in these latter two species, especially for deficiencies of nitrogen, phosphorus, and sulfur.
5. *Mobility of the elements.* The "mobile elements" nitrogen, phosphorus, and potassium can move readily out of the leaf or stem in which they are initially incorporated. Especially in case of deficiency, they migrate from older tissue into newly formed leaves, buds, or roots. Magnesium is also mobile in many plants, but seems to be only

Table 1. Summary of mineral deficiency symptoms in Douglas-fir.

Nitrogen (N)	Light green foliage; in severe deficiency needles small and yellow, terminal growth restricted, and older foliage turning brown and shedding prematurely.
Phosphorus (P)	Unspecific symptoms characteristic of a mobile element—browning and dying of older needles.
Potassium (K)	Tips of needles become brown, starting in the older foliage; this necrosis progresses back from the tips with severe deficiency.
Calcium (Ca)	Dying of terminal buds and some lateral buds.
Magnesium (Mg)	Beginning with the older needles, the tips turn brown and there is a yellow region between the brown tip and the green basal portion; this progresses until the entire needle is brown.
Sulfur (S)	Upper needles yellowish; older needles still green.
Boron (B)	Terminal buds dying; foliage exceptionally dark green.
Iron (Fe)	Upper (younger) foliage bright yellow; older foliage remains green.

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