Chapter 18
Evaluating Regeneration Success

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Abstract

In evaluating regeneration success the forest manager is faced with two related decisions: (a) choosing an inventory method that will give reliable information on seedling survival, seedling condition, and spatial distribution of surviving seedlings; and (b) using that information to determine the future of the stand (e.g., whether or not to start over). Five types of inventory methods are described and illustrated herein — plot count, distance, quadrant sampling, stocked quadrant, and sequential sampling. These methods provide information on seedling survival and stocking needed to determine regeneration success. However, these data alone are not sufficient and should be supplemented by currently available growth and yield models coupled with appropriate financial data to obtain the best possible management decision.

18.1 Introduction

This chapter deals with one of the most perplexing problems facing the forest manager — how to obtain an effective, usable evaluation of regeneration success. For most industrial and public lands, decisions about how many trees to plant and at what spacings may be based on sound biological and economic considerations (see chapter 15, this volume). However, near perfect survival is seldom achieved. For example, 16 years of operational planting of loblolly pine (*Pines taeda* L.) on the Yazoo-Little Tallahatchie flood prevention project showed a median survival of 73% (range, 55 to 90%); survival exceeded 80% in only 3 of the 16 years [22]. Similar results were obtained from a 3-year study of operational plantings on cutover sites in the Virginia Coastal Plain [12]. Therefore, the forest manager is faced with two related decisions: (a) choosing an inventory (survey) method that will give reliable information on seedling survival, overall seedling condition, and spatial distribution of surviving seedlings; and (b) using that information to determine the future financial yield of the stand (e.g., whether or not to start over).

In this chapter, we describe and evaluate methods that could be used to determine early survival and stocking adequacy and show how that information can help foresters make decisions concerning future stand management — both biological feasibility and economic environment must be taken into account in the decisionmaking process. Although we emphasize evaluation of planted pine seedlings, most of the methods also can be used for assessing stands originating by direct seeding or natural regeneration. Where appropriate, differences are discussed.

18.2 Need for and Timing of Evaluation

The regeneration phase is the most critical time in the life of any stand. Not only are seedling losses and stand failure most likely to occur at that time, but the results probably will dictate future silvicultural treatments. In addition, stand regeneration usually represents a sizable financial investment that must be compounded for a long period, often at high interest rates; this is especially true for plantations for which the cost of site preparation is considered part of the cost of regeneration. Furthermore, regeneration failures need to be remedied as soon as possible. Delay usually necessitates the use of more expensive corrective measures and reduces the opportunity to capture the initial regeneration investment (for more on economics, see chapter 2, this volume).

The above considerations illustrate the need for an effective evaluation of regeneration success, but the timing of that evaluation also is critical and is determined primarily by the pattern of seedling mortality. The first few months in the field are crucial in the life of a southern pine seedling especially if it starts from seed. Seedlings can die from numerous biotic and abiotic agents, but weather usually is the most critical factor affecting both natural and artificial regeneration. For seedlings established by direct seeding, Derr and Mann [8] found that mortality may average <10% on good sites where summer rainfall is well distributed, but may reach 70% in a year in the West Gulf region, where droughts of 4 to 8 weeks' duration are common. For planted southern pine seedlings, survival generally is much better (Fig. 18.1), but mortality is highest in the first spring and summer following planting. Planted seedlings are likely to maintain a near constant level of survival from the end of the first or second year until their

M.L. Duryea & P.M. Dougherty (eds), Forest Regeneration Manual, pp. 321–331.

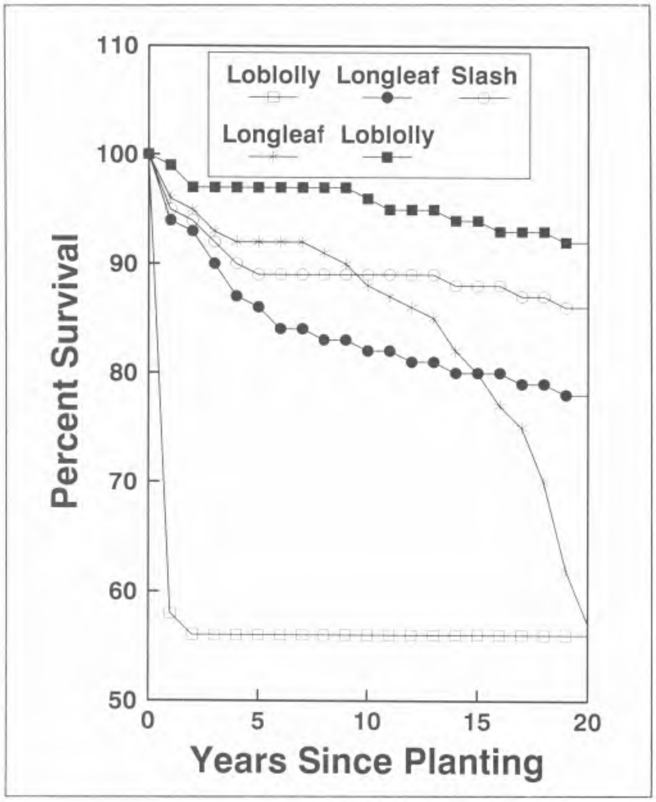

Figure 18.1. Typical survival patterns of planted loblolly, slash, and longleaf pines, Bogalusa, Louisiana. The two longleaf plantations had almost identical initial survival, but their mortality from brown-spot needle disease and other causes differed conspicuously during the next 19 years. One loblolly stand had high initial survival and the other low (adapted from [20]).

crowns have closed [20]. Exceptions occur with longleaf pine *(Pinus palustris* Mill.) in heavy zones of uncontrolled brown-spot needle blight *(Scirrhia acicola)* or with slash pine *(Pinus elliottii* Engelm.) in heavy zones of fusiform rust *(Cronartium quercuum;* see also chapter 20, this volume).

For plantations, information on mortality patterns indicates that the best time to evaluate seedling survival is in the fall after the first growing season. Sequential sample plots may be installed just after planting and before drought occurs to assess planting technique and spacing (see 18.4.5), but they do not give information on establishment success and initial stocking. More frequent surveys are needed during the first year if seedling survival is a major problem. For example, seedling damage (e.g., by cattle or insects) may require monitoring around midseason. Moreover, severe biotic or abiotic problems after the first growing season may make a second-year survey desirable. For direct seeding, two [8] or four [6] surveys are recommended the first year. The final survey — the most important — is used to evaluate seedling success. Others give information on seed and seedling losses and initial seedling establishment. For natural regeneration, more than one survey may be needed because stands can regenerate over a period of several years. Regardless of stand origin, repeated surveys, although providing detailed evaluation data, represent early personnel costs that will loom large when compounded to rotation age.

18.3 Desired Information

In surveys done for most management purposes, the emphasis is on seedling counts to determine survival and/or stocking. These two terms are sometimes used interchangeably, but should not be. Survival refers to the living trees at a given time and is expressed as a percentage of those planted or germinating. Stocking, on the other hand, refers to the number of living seedlings per unit area (e.g., number per ac or hectare) or, in some cases, to the percentage of sample plots containing live seedlings. Information on survival may be useful in determining the effectiveness of a planting operation, identifying regeneration problems, or verifying that the contractor planted the specified number of seedlings, but that on stocking generally is used to determine overall regeneration success.

Information on survival and stocking alone is not sufficient to make a decision about regeneration success. Unless a stand is carefully stratified (see 18.4.1), poor stocking in one area and good stocking in another may imply an acceptable overall average whereas, in reality, some parts of the stand should be regenerated again (restarted). Therefore, some indication of spacing per seedling or distribution of surviving seedlings also is needed and can be obtained by certain inventory methods described later.

In addition, it may be desirable to obtain information on other site and seedling conditions, for example, causes of mortality, damage, or disease, or hardwood competition. Such data can be obtained either in connection with the regeneration survey or (if more details are needed on species, size, and numbers) separately.

18.4 Inventory Methods

18.4.1 Plot Count

Counting surviving seedlings on randomly or systematically located fixed-area plots is an easy, accurate means of determining the number of potential crop trees per unit area. The main disadvantage of plot counts, however, is the lack of information on spatial distribution of seedlings. For example, despite a seedling count meeting management goals, seedlings may be clumped into highly competitive groups that ultimately yield only a few badly distributed crop trees at harvest if the method is applied blindly. In part, this failing can be overcome by carefully stratifying the study area into homogeneous classes based on survival density and seedling distribution and surveying each class separately. Topography, aspect, drainage class, and soil type are logical stratification variables. However, the combination of these variables that will generate the best outcome can only be established through experience and *a priori* observation of the impact that each variable has on seedling survival and spatial distribution or, even better, through an objective volume and cash-flow analysis (see 18.5.2).

Once the plot counts have been made and recorded within a class, the statistical calculations are straightforward. First, the mean number of seedlings/unit area (-x), standard deviation/unit area (s), and standard error of the mean/unit area (s_e) are evaluated, respectively:

$$\bar{x} = \sum_{i=1}^{n} x_i/(an) , \quad (1)$$

$$s = a^{-1} \left\{ \left[\sum_{i=1}^{n} x_i^2 - \left(\frac{\sum x_i}{n} \right)^2 \right] /(n-1) \right\}^{1/2} , \quad (2)$$

and

$$s_e = [s/(n)^{1/2}](1 - n/N)^{1/2} , \quad (3)$$

where *t/* is total number of plots on which counts were taken, x_i is seedling count/plot, *a* is plot size (typically, 1/50- or I/100-ac, or 0.008- or 0.004-ha), and *N* is total number of plots of size *a* in the class (closest integer value to *Ala,* where A is total area of the class expressed in the same units as plot size).

The lower confidence interval on the true mean number of seedlings/unit area (ii) with percent confidence p is established with:

$$\mu \geq \bar{x} - ts_e , \quad (4)$$

where *t* is the value from a two-sided Student's *t*-distribution table with *a* —1 degrees of freedom at a probability of 2(1 —p/100).

For example, Table 18.1 displays the surviving-seedling counts made on 60 1/50-ac (0.008-ha) plots randomly distributed in a I-year-old 100-ac (40.5-ha) loblolly pine plantation. The estimated mean number of surviving seedlings/ac (ha) is

$$\bar{x} = \frac{13 + 12 + \cdots + 9}{(60)(1/50)} = \frac{50(635)}{60} = 529.2(1,307.7).$$

The estimated standard deviation of the number of seedlings/ac (ha) (from Equation (2)) is

$$s = 50^{-1} \left\{ \left[(13^2 + 12^2 + \cdots + 9^2) - \frac{(13 + 12 + \cdots + 9)^2}{60} \right] /(60-1) \right\}^{1/2} = \frac{50}{59} \left(7,383 - \frac{635^2}{60} \right)^{1/2} = 21.8(53.9).$$

The standard error of the mean number of seedlings/ac (ha) (from Equation (3)), where the total number of plots is 5,000, is

$$s_e = [21.8/(60)^{1/2}](1 - 60/5,000)^{1/2} = 3.07 \ (7.59).$$

From Table 18.2, the t-value for 59 degrees of freedom at a probability of 2(1 - 95/100) = 0.10 is 1.671. Therefore, from Equation (4):

$$\mu \geq 529.2 - (1.671)3.07 = 524.1 \ (1,295.1) \text{ seedlings/ac (ha).}$$

Before plots are located in the field and survivors counted, the number of sample plots required in each class to estimate the mean within a pre-established maximum allowable error should be calculated. By making this calculation, foresters often can avoid the need to re-enter the area and install additional plots if the confidence interval around the mean is too wide to make a sound decision on regeneration success. Where the total number of plots is expected to exceed 100, the number of plots/class *(a)* required to be *p* percent confident that the estimated mean number of seedlings/unit area will be within —*E* seedlings of the true mean is calculated as:

$$n = 1/[(E/ts)^2 + 1/N] \quad (5)$$

where the t-value has infinite degrees of freedom and a 2(1 —*p*/ I 00) probability of a greater value, and *s* is our best educated guess on the expected standard deviation.

Where the total number of plots is not expected to exceed 100, iterative substitution must be applied to calculate the sample size *(n).* This is done by successively substituting the t-value corresponding to each *a* calculated from Equation (5) back into the equation until the *a* value does not change. To illustrate, suppose a I-year-old 250-ac (101-ha) pine plantation is to be surveyed using 1/10-ac (0.04-ha) plots, the stated precision for surveys is to be 95% confident of being within 10 seedlings/ac (25/ha), and, from previous experience with similar plantations, the expected standard deviation is about 50 seedlings/ac

Table 18.1. Surviving seedlings on 60 1/50-ac plots randomly distributed in a 1-year-old 100-ac loblolly pine plantation, as determined by plot counts.

Plot no.	Count	Plot no.	Count	Plot no.	Count
1	13	21	10	41	12
2	12	22	11	42	13
3	6	23	10	43	12
4	3	24	13	44	6
5	3	25	15	45	10
6	3	26	13	46	9
7	8	27	10	47	15
8	9	28	14	48	15
9	6	29	11	49	14
10	11	30	13	50	13
11	10	31	8	51	13
12	8	32	9	52	16
13	11	33	14	53	13
14	14	34	11	54	13
15	10	35	12	55	16
16	7	36	12	56	11
17	10	37	9	57	11
18	8	38	9	58	18
19	6	39	11	59	13
20	8	40	12	60	9

Table 18.2. Distribution of t (adapted from [9]).

Degrees of freedom	Probability								
	0.5	0.4	0.3	0.2	0.1	0.05	0.02	0.01	0.001
1	1.000	1.376	1.963	3.078	6.314	12.706	31.821	63.657	636.619
2	0.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925	31.598
3	0.765	0.978	1.250	1.638	2.353	3.182	4.541	5.841	12.941
4	0.741	0.941	1.190	1.533	2.132	2.776	3.747	4.604	8.610
5	0.727	0.920	1.156	1.476	2.015	2.571	3.365	4.032	6.859
6	0.718	0.906	1.134	1.440	1.943	2.447	3.143	3.707	5.959
7	0.711	0.896	1.119	1.415	1.895	2.365	2.998	3.499	5.405
8	0.706	0.889	1.108	1.397	1.860	2.306	2.896	3.355	5.041
9	0.703	0.883	1.100	1.383	1.833	2.262	2.821	3.250	4.781
10	0.700	0.879	1.093	1.372	1.812	2.228	2.764	3.169	4.587
11	0.697	0.867	1.088	1.363	1.796	2.201	2.718	3.106	4.437
12	0.695	0.873	1.083	1.356	1.782	2.179	2.681	3.055	4.318
13	0.694	0.870	1.079	1.350	1.771	2.160	2.650	3.012	4.221
14	0.692	0.868	1.076	1.345	1.761	2.145	2.624	2.977	4.140
15	0.691	0.866	1.074	1.341	1.753	2.131	2.602	2.947	4.073
16	0.690	0.865	1.071	1.337	1.746	2.120	2.583	2.921	4.015
17	0.689	0.863	1.069	1.333	1.740	2.110	2.567	2.898	3.965
18	0.688	0.862	1.067	1.330	1.734	2.101	2.552	2.878	3.922
19	0.688	0.861	1.066	1.328	1.729	2.093	2.539	2.861	3.883
20	0.687	0.860	1.064	1.325	1.725	2.086	2.528	2.845	3.850
21	0.686	0.859	1.063	1.323	1.721	2.080	2.518	2.831	3.819
22	0.686	0.858	1.061	1.321	1.717	2.074	2.508	2.819	3.792
23	0.685	0.858	1.060	1.319	1.714	2.069	2.500	2.807	3.767
24	0.685	0.857	1.059	1.318	1.711	2.064	2.492	2.797	3.745
25	0.684	0.856	1.058	1.316	1.708	2.060	2.485	2.787	3.725
26	0.684	0.856	1.058	1.315	1.706	2.056	2.479	2.779	3.707
27	0.684	0.855	1.057	1.314	1.703	2.052	2.473	2.771	3.690
28	0.683	0.855	1.056	1.313	1.701	2.048	2.467	2.763	3.674
29	0.683	0.854	1.055	1.311	1.699	2.045	2.462	2.756	3.659
30	0.683	0.854	1.055	1.310	1.697	2.042	2.457	2.750	3.646
40	0.681	0.851	1.050	1.303	1.684	2.021	2.423	2.704	3.551
60	0.679	0.848	1.046	1.296	1.671	2.000	2.390	2.660	3.460
120	0.677	0.845	1.041	1.289	1.658	1.980	2.358	2.617	3.373
∞	0.674	0.842	1.036	1.282	1.645	1.960	2.326	2.576	3.291

(I 24/ha). Thus, with iterative substitution, the first estimate of the required sample size is:

$$n = 1/\{[10/(1.645 \times 50)]^2 + 1/2{,}500\} = 66$$

Because the number of degrees of freedom for the estimated sample size differs from the infinite degrees of freedom assumed for the first estimate of n given above, n must be repeatedly calculated with a different r-value until no change in n occurs:

$$n = 1/\{[10/(1.670 \times 50)]^2 + 1/2{,}500\} = 68$$
$$n = 1/\{[10/(1.670 \times 50)]^2 + 1/2{,}500\} = 68.$$

Although plot counts do not consider the spatial distribution of seedlings, careful stratification of the study area into homogeneous classes can overcome many of the objections to this method. After stratification, the plot counts provide an accurate, reliable estimate of the numbers of seedlings/unit area. When site-quality information is coupled with good yield estimates, an economic analysis can be applied to determine if regeneration is sufficient to meet management goals (see 18.5.2). In classes with poorly distributed seedlings, growth and yield estimates may need to be reduced, particularly when thinning is required, because most growth and yield simulators are developed from data in stands with good distribution of surviving seedlings.

18.4.2 Distance

Point-to-nearest-plant and plant-to-nearest-neighboring-plant distance methods for measuring numbers and dispersion of naturally regenerating seedlings have been investigated by several researchers [3, 7, 16]. In the point-to-plant procedure, random points are located within the study area, and the distance from the point to the nearest plant is recorded. The plant-to-plant procedure first requires a complete enumeration of the plant population; that is, each plant must be labeled clearly before sample selection. Plants then are selected randomly from the enumerated population and located, and the distance to the nearest neighbor of each is recorded.

The point-to-plant method is particularly appealing for regeneration surveys because the measured distances represent radii of unoccupied circles (open space). It is thus possible to tabulate the distribution of open spaces and decide if there are too many large ones for satisfactory stocking.

When the regenerating seedlings are distributed randomly, the distribution of distance (point-to-plant, or plant-to-plant) has the exponential class probability density function (Fig. 18.2):

$$f(r) = 2\tau r e^{-\tau r^2} \quad 0 \le r \le \infty$$
$$= 0 \quad \text{elsewhere,} \qquad (6)$$

where r is a random variable representing distance, the Poisson parameter τ is the mean number of individuals/circle of unit radius (area of = π 3.14159 units), and e is the base of the natural logarithm. Moore [15] showed from Equation 6 that an unbiased estimate of τ is:

$$= (n - 1)/n\overline{w} \qquad (7)$$

where n is the number of sample points, $\overline{w}$ is the mean squared distance from point to plant or plant to plant,

$$\overline{w} = \sum_{i=1}^{n} r_i^2/n \; ,$$

and r_i is the distance from the its' point to the nearest plant or from a plant to its nearest neighbor.

Because τ estimates the mean number of individuals/circle of unit radius (a circle of it square units), it must be multiplied by the appropriate conversion factor (CF) to obtain the mean number of seedlings/unit area (ac, hectare, etc.). Selected CFs are listed below:

Distance unit	Land area unit	Conversion factor
Meter	Hectare	3,183.099
Centimeter	Hectare	31,830,988.61
Feet	Acre	13,865.579
Inches	Acre	1,996,643.324

Additional CFs can be derived with the equation

$$CF = S/\pi \qquad (8)$$

where S is the number of square distance measurement units/unit of land area, and π(= 3.14159) is the number of square distance measurement units in a circle of unit radius. For example, if distance is measured in feet and we want the mean number of seedlings/ac, the conversion factor would be 43,560/3.14159 = 13,865.579 (1 ac contains 43,560 ft^2).

To illustrate the computations, consider the 100 point-to-plant distances recorded for a naturally regenerated loblolly pine stand (Table 18.3). The mean squared distance from point to nearest plant is

Table 18.3. Distance from random point to nearest neighboring plant — for 100 measurements recorded in a naturally regenerated 3-year-old loblolly pine stand.

Distance, ft				
7.7	10.8	8.2	8.2	7.0
4.7	4.2	7.1	7.3	5.6
10.6	4.6	9.2	7.0	3.6
5.4	4.1	4.5	4.0	2.3
4.8	6.1	4.0	2.6	7.3
7.3	1.8	3.2	4.8	4.2
1.8	5.4	12.8	5.8	8.0
10.2	5.0	0.8	6.6	6.4
5.2	6.5	2.6	6.5	6.0
3.4	5.0	2.8	8.0	5.6
4.9	6.5	6.9	4.4	8.0
7.6	8.3	11.0	5.6	4.1
1.8	6.1	9.8	1.0	6.9
5.6	2.3	10.7	1.8	6.3
6.7	2.3	8.0	5.4	.5
3.4	3.8	6.8	7.2	5.9
8.3	3.6	2.6	2.7	3.0
4.1	6.5	3.6	5.5	9.31
4.4	3.5	8.9	6.0	4.1
7.9	0.3	6.1	2.0	4.4

$$\overline{w} = (7.7^2 + 4.7^2 + \ldots + 4.4^2)/100 = 3{,}702.78/100 = 37.02 \text{ ft.}$$

Thus, the mean number of seedlings/circle of 1-ft unit radius (or 3.14159 ft^2) is

$$\tau = [(100 - 1)/100](1/37.02) = 0.02674,$$

and the number of seedlings/ac is

$$(13{,}865.579)\tau = (13{,}865.579)(0.02674) = 370.8.$$

When the regenerating seedlings are not distributed randomly, τ will be biased. If the population is uniformly distributed, as in plantations, the estimate will be high; if the population tends to be contiguous, as in shelterwoods, the estimate will be low [16, 17]. Batchler [3] investigated these biases and devised correction procedures based on distances to the second nearest neighbor.

One problem that plagues distance procedures is that unfortunately there is no easy test for a random spatial distribution. Comparing the theoretical distributions of distances from a random population to their corresponding empirical distributions does not work because many nonrandom spatial arrangements can yield the same distribution. In naturally or artificially seeded stands, it usually can be safely assumed that the spatial arrangement will be nearly random.

The distances (r_i) from point to plant or plant to plant represent, on the average, circles of area πr_i^2 available for a plant to occupy. Tabulation of these open spaces into a frequency diagram (Table 18.4) can provide valuable insight into the distribution of available growing area. If the percentage or number of seedlings having too large an

Table 18.4. Example distribution of the frequency of available open space for seedling growth.

Open space, ft^2	Proportion	Seedlings/ac
66 × 90	0.0513	15.4
90 × 110	0.1353	40.6
110 × 130	0.2033	61.0
130 × 150	0.2107	63.2
150 × 170	0.1907	57.2
170 × 190	0.1073	32.2
190 × 210	0.0560	16.8
210 × 230	0.0187	5.6
230 × 250	0.0133	3.4
250 × 270	0.0067	2.0
270 × 290	0.0033	1.0
290 × 310	0.0027	0.8

open-space frequency exceeds the established minimum, the regeneration phase should be restarted. For example, if it takes 200 fully occupied areas for successful regeneration and a forester has 300 trees/unit, 50 of which have too much space, the regeneration phase would not be restarted. However, what constitutes a fully occupied area depends on management objectives. A larger open space is desirable for growing sawtimber than for growing pulpwood. Because of the tremendous variation in acceptable product yield between organizations, guidelines on open space would have to be established on an individual basis.

18.4.3 Quadrant Sampling

Quadrant sampling, used by ecologists to study the numbers and distribution of individuals in natural populations, also has been evaluated for and applied to the problem of assessing regeneration success. The procedure consists of distributing randomly (completely or along transects) within an area a large number of sample quadrants (plots), typically 1 to 5 milliac (4.05 to 20.23 m^2), and counting the number of seedlings on each quadrant.

The mean number and variance of seedlings/quadrant are calculated, respectively, with

$$\bar{x} = \sum_{i=1}^{n} x_i/n \, , \tag{9}$$

and

$$s^2 = \left(\sum_{i=1}^{n} x_i^2 - n\bar{x}^2\right)/(n-1). \tag{10}$$

In the special case in which individuals are distributed randomly, the quadrant counts have a Poisson distribution with parameters equal to the mean number of seedlings/quadrant:

$$P(x) = \frac{\mu^x e^{-\mu}}{x!}\, , \qquad x = 0,\ 1,\ 2, \cdots \, , \tag{11}$$

$$0 = \text{elsewhere}$$

where $P(x)$ is the probability of a quadrant having x seedlings, and x is a random variable representing quadrant counts. Because the variance of the Poisson distribution is equal to its mean, the variance of the theoretical mean (t) compared to the variance of the actual sample mean forms a randomness index

$$I = \mu/s^2. \tag{12}$$

If I equals 1, the spatial distribution is random; if I is > 1, the distribution tends to be uniform; if I is < 1, the distribution is clumpy. From the forest-management viewpoint, a clumpy distribution is the worst case, a uniform one the most desirable. In general, however, the best that can be expected is a random spatial distribution of seedlings.

Using the data from the 60 25-milliac (101-m^2) count plots shown in Table 18.5, the mean number of seedlings/quadrant (from Equation (9)) is

$$\bar{x} = (6 + 10 + \cdots + 7)/60 = 463/60 = 7.72.$$

The variance of the seedling counts/quadrant (from Equation (10)) is

$$s^2 = [(6^2 + 10^2 + \ldots + 7^2) - (60)(7.72^2)]/(60-1)$$
$$= [4{,}131 - 3{,}575.90]/59 = 9.41.$$

Assuming the individuals are distributed randomly, = 7.72, and the randomness index (from Equation (12)) is 7.72/9.41 = 0.82. Because I = 0.82 is close to but < 1, we would conclude that the spatial distribution is nearly random but slightly clumpy.

A chi-square test of the hypothesis that the quadrant counts follow a Poisson distribution can be performed by generating a theoretical distribution from Equation (11) with II and computing the chi-square test statistic

$$T = \sum_{x=0}^{x=k}\{[\hat{P}(x) - P(x)]/P(x)\}^2 \tag{13}$$

where $P(x)$ is the expected proportion of plots having x seedlings (calculated from Equation (11)), $P(x)$ is the observed proportion of plots having x seedlings, and k is the largest plot count having significant probability. If T exceeds the value from a chi-square distribution with k degrees of freedom at a probability level of, say, 0.05, the hypothesis that the quadrant counts follow a Poisson distribution would be rejected. However, failure to reject the hypothesis does not imply a random spatial distribution. It only demonstrates that the quadrant counts follow a Poisson distribution because many nonrandom spatial arrangements can yield such a distribution.

To calculate T for the data in Table 18.5:

$$P(0) = (7.72^0 e^{-7.72})/(1) = 0.0004\, ,$$

$$\hat{P}(0) = 0/60 = 0.0000$$

$$P(1) = (7.72^1 e^{-7.72})/(1) = 0.0034\, ,$$

$$\hat{P}(1) = 0/60 = 0.0000$$

$$P(2) = (7.72^2 e^{-7.72})/(2 \times 1) = 0.0132\ ,$$

$$\hat{P}(2) = 1/60 = 0.0167$$

$$P(3) = (7.72^3 e^{-7.72})/(3 \times 2 \times 1) = 0.0340\ ,$$

$$\hat{P}(3) = 5/60 = 0.0833$$

$$P(13) = (7.72^{13} e^{-7.72})/(13 \times 12 \cdots \times 1) = 0.0247$$

$$\hat{P}(13) = 0/60 = 0.0000$$

$$P(14) = (7.72^{14} e^{-7.72})/(14 \times 13 \cdots \times 1) = 0.013$$

$$\hat{P}(14) = 3/60 = 0.0500$$

$$P(15+) = -\sum_{x=0}^{14} P(x) = 1 - 0.9868 = 0.0132\ ,$$

$$\hat{P}(15+) = 0/60 = 0.0000$$

$$T = [(0.0000 - 0.0004)/0.0004]^2 + [(0.0000 - 0.0034)/0.0034]^2 + \cdots + [(0.0500 - 0.0136)/0.0136]^2 + [(0.0000 - 0.0132)/0.0132]^2 = 14.91.$$

The test statistic $T = 14.91$ does not exceed the critical value of 25.00 for 15 degrees of freedom at a probability level of 0.05 (Table 18.6), so we cannot reject the hypothesis that the quadrant counts are Poisson distributed.

18.4.4 Stocked Quadrant

In assessing natural regeneration success, foresters are concerned primarily with the number and spatial distribution of trees at harvest. Many trees may be present but so poorly distributed that the stand is understocked after thinning. Recognizing this, foresters developed the stocked quadrant method to emphasize the distribution, rather than the total number, of trees.

Table 18.5. Seedling counts from 60 25-milliac quadrants in a 3-year-old naturally regenerated loblolly pine stand.

Plot no.	Count	Plot no.	Count	Plot no.	Count
1	6	21	14	41	5
2	10	22	7	42	12
3	7	23	6	43	4
4	7	24	11	44	10
5	12	25	7	45	2
6	8	26	6	46	12
7	5	27	3	47	10
8	14	28	8	48	7
9	7	29	12	49	10
10	7	30	2	50	3
11	5	31	11	51	10
12	4	32	7	52	14
13	9	33	9	53	9
14	12	34	7	54	8
15	3	35	6	55	10
16	6	36	7	56	9
17	6	37	6	57	6
18	8	38	5	58	3
19	10	39	9	59	3
20	8	40	12	60	7

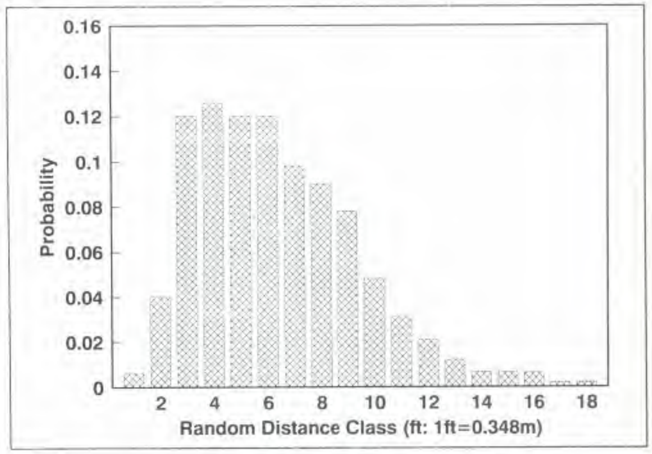

Figure 18.2. Typical probability histogram of distance from random point to nearest neighboring plant derived from 2,000 measurements in a 3-year-old naturally regenerated loblolly pine stand.

The stocked quadrant method consists of locating a series of square or circular quadrants within the study area and noting the presence or absence of at least one well-established seedling. Stocked quadrant data, therefore, attempt to measure the percentage of nonoverlapping quadrants that could be occupied at stand maturity. If, in addition, the numbers of seedlings in each quadrant are tallied, the mean number of individuals/unit area also can be estimated easily.

In application, the size of the quadrant chosen most often has been determined by the number of well-distributed seedlings required at establishment to achieve full stocking after thinning. For example, if 500 well-distributed seedlings/ac (1,235/ha) are desired, a 2-milliac (8-m^2) quadrant would be used because each seedling would occupy 87.3 ft^2 (8.1 m^2) — that is, 9.3 x 9.3 ft^2, or 2.83 x 2.83 m^2, which is 2 milliac. The stocking percentage then could be correlated to growth and yield as well as economic information to determine regeneration success or failure.

18.4.5 Sequential Sampling

Sequential (or staked point) sampling refers to a procedure by which trees, seed plots, or plots are repeatedly examined over time, not statistical sequential sampling as developed by Wald [19]. The objective usually is not to estimate the numbers of surviving seedlings, but rather to examine the reforestation process itself — planting-crew performance and seedling quality and performance in plantations, and uniformity of seeding, germination, and survival in direct-seeded or naturally seeded areas.

The main problem with sequential sampling is the cost

Table 18.6. Accumulative distribution of chi-square (adapted from [9].

Degrees of freedom	Probability of a greater value												
	0.995	0.990	0.975	0.950	0.900	0.750	0.500	0.250	0.100	0.050	0.025	0.010	0.005
1	–	–	–	–	0.02	0.10	0.45	1.32	2.71	3.84	5.02	6.63	7.88
2	0.01	0.02	0.05	0.10	0.21	0.58	1.39	2.77	4.61	5.99	7.38	9.21	10.60
3	0.07	0.11	0.22	0.35	0.58	1.21	2.37	4.11	6.25	7.81	9.35	11.34	12.84
4	0.21	0.30	0.48	0.71	1.06	1.92	3.36	5.39	7.78	9.49	11.14	13.28	14.86
5	0.41	0.55	0.83	1.15	1.61	2.67	4.35	6.63	9.24	11.07	12.83	15.09	16.75
6	0.68	0.87	1.24	1.64	2.20	3.45	5.35	7.84	10.64	12.59	14.45	16.81	18.55
7	0.99	1.24	1.69	2.17	2.83	4.25	6.35	9.04	12.02	14.07	16.01	18.48	20.28
8	1.34	1.65	2.18	2.73	3.49	5.07	7.34	10.22	13.36	15.51	17.53	20.09	21.96
9	1.73	2.09	2.70	3.33	4.17	5.90	8.34	11.39	14.68	16.92	19.02	21.67	23.59
10	2.16	2.56	3.25	3.94	4.87	6.74	9.34	12.55	15.99	18.31	20.48	23.21	25.19
11	2.60	3.05	3.82	4.57	5.58	7.58	10.34	13.70	17.28	19.68	21.92	24.72	26.76
12	3.07	3.57	4.40	5.23	6.30	8.44	11.34	14.85	18.55	21.03	23.34	26.22	28.30
13	3.57	4.11	5.01	5.89	7.04	9.30	12.34	15.98	19.81	22.36	24.74	27.69	29.82
14	4.07	4.66	5.63	6.57	7.79	10.17	13.34	17.12	21.06	23.68	26.12	29.14	31.32
15	4.60	5.23	6.27	7.26	8.55	11.04	14.34	18.25	22.31	25.00	27.49	30.58	32.80
16	5.14	5.81	6.91	7.96	9.31	11.91	15.34	19.37	23.54	26.30	28.25	32.00	34.27
17	5.70	6.41	7.56	8.67	10.09	12.79	16.34	20.49	24.77	27.59	30.19	33.41	35.72
18	6.26	7.01	8.23	9.39	10.86	13.68	17.34	21.60	25.99	28.87	31.53	34.81	37.16
19	6.84	7.63	8.91	10.12	11.65	14.56	18.34	22.72	27.20	30.14	32.85	36.19	35.58
20	7.43	8.26	9.59	10.85	12.44	15.45	19.34	23.83	28.41	31.41	34.17	37.57	40.00
21	8.03	8.90	10.28	11.59	13.24	16.34	20.34	24.93	29.62	32.67	35.48	38.93	41.40
22	8.64	9.54	10.98	12.34	14.04	17.24	21.34	26.04	30.81	33.92	36.78	40.29	42.80
23	9.26	10.20	11.69	13.09	14.85	18.14	22.34	27.14	32.01	35.17	38.08	41.64	44.18
24	9.89	10.86	12.40	13.85	15.66	19.04	23.34	28.24	33.20	36.42	39.36	42.98	45.56
25	10.52	11.52	13.12	14.61	16.47	19.94	24.34	29.34	34.68	37.65	40.65	44.31	46.93
26	11.16	12.20	13.84	15.38	17.29	20.84	25.34	30.43	35.56	38.89	41.92	45.64	48.29
27	11.81	12.88	14.57	16.15	18.11	21.75	26.34	31.53	36.74	40.11	43.19	46.96	49.64
28	12.46	13.56	15.31	16.93	18.94	22.66	27.34	32.62	37.92	41.34	44.46	48.28	50.99
29	13.12	14.26	16.05	17.71	19.77	23.57	28.34	33.71	39.09	42.56	45.72	49.59	52.34
30	13.79	14.95	16.79	18.49	20.60	24.48	29.34	34.80	40.26	43.77	46.98	50.89	53.67
40	20.71	22.16	24.43	26.51	29.05	33.66	39.34	45.62	51.80	55.76	59.34	63.69	66.77
50	27.99	29.71	32.36	34.76	37.69	42.94	49.33	56.33	63.17	67.50	71.42	76.15	79.49
60	35.53	37.48	40.48	43.19	46.46	52.29	59.33	66.98	74.40	79.08	83.30	88.38	91.95
70	43.28	45.44	48.76	51.74	55.33	61.70	69.33	77.58	85.53	90.53	95.02	100.42	104.22
80	51.17	53.54	57.15	60.39	64.28	71.14	79.33	88.13	96.58	101.88	106.63	112.33	116.32
90	59.20	61.75	65.65	69.13	73.29	80.62	89.33	98.64	107.56	113.14	118.14	124.12	128.30
100	67.33	70.06	74.22	77.93	82.36	90.13	99.33	109.14	118.50	124.34	129.56	135.81	140.17

and effort required to repeatedly examine trees or plots. When staked plots or points are combined with survival survey plots, however, information on both survival and the reforestation process can be obtained. The cost of sequential sampling probably is justified only on a limited basis to identify specific regeneration problems so corrective action may be taken.

18.5 Survival Adequacy

18.5.1 Management Objectives

After data from the regeneration survey are obtained, the manager may be faced with a second, and sometimes very difficult, decision if survival or stocking is less than desirable. For pine plantations, there are essentially three options: (1) accept less than full stocking for the early years of the rotation, (2) replace some or all of the dead seedlings by interplanting, or (3) replant the entire area. In most cases the choice will be between (1) and (3) because interplanting usually is an ineffective way of increasing stocking [1, 4, 11, 18, 20, 21]. Even if interplanting is done after one growing season, the younger seedlings usually will be relegated to a subordinate position in the crown canopy and will produce little merchantable volume. One exception to this may be the case in which the survey indicates mortality on fairly large areas within the plantation; in such openings, early growth of the "replants" would not be suppressed by older seedlings. In any case, replacement seedlings should not be planted within about 20 ft (6.1 m) of established seedlings [2].

Assuming fairly uniform distribution of the surviving seedlings, the question then becomes, "What is the lowest number of seedlings/ac that can be accepted before starting over?" Balmer and Williston [2] suggest that if 300 or more well-distributed seedlings/ac (740/ha) survive, replanting will be too costly. However, that decision should be influenced greatly by management objectives. For example, if pulpwood is the desired product and the intended stocking is 600 seedlings/ac (1,482/ha), initial survival of 300 and 200/ac (741 and 494/ha) would reduce cordwood production by 20 and 30%, respectively, at age 20 [5]. It seems likely, therefore, that replanting would be advisable, especially if stocking is only 200 seedlings/ac. On the other hand, if sawtimber is the desired product, even 200/ac might be adequate. In either case, prevalence of diseases such as brown-spot, needle blight, and fusiform rust must be considered. Xydias et al. [23] suggest that for slash pine in high-hazard fusiform rust areas, foresters should hesitate to accept fewer than 400 seedlings/ac (988/ha). Ultimately, the assessment of stocking adequacy should be based on an economic analysis that takes into account such variables as trees/area, site index, and rotation and stand age.

18.5.2 Growth and Yield Simulation and Financial Analysis

Establishing arbitrary regeneration restart points based on minimum numbers of seedlings per unit area often can and does result in restarting the regeneration phase unnecessarily or failing to restart stands that will not meet management objectives. The harvest potential is a complex interaction of numbers per unit area, spatial distribution, and site quality, which is best tested for each individual case by a growth and yield simulation. Model projections then should be coupled with financial data to complete the analysis. A good example of the combined growth and yield-financial approach using area potentially available (APA) is presented by Matney and Hodges [13].

The first step is to select a growth and yield model. To do this, foresters should consider the applicability of the database to the specific condition of the stand, as well as the type of model. Stand-level and diameter-distribution models provide good information on yield but do not evaluate the effects of spatial distribution as the distance-dependent individual-tree models do. The second step is to update or develop price and management cost data that accurately reflect the local market area. This paper [13] also describes a negative binomial approach to sampling survival in plantations that is worth investigating.

Once the growth and yield model and financial data are selected, and several different silvicultural regimes for the regeneration area proposed, the economic return for each regime should be calculated (see chapter 2, this volume, for details on economic analyses). Each regime should include the value of the present regeneration plus the original regeneration cost compounded to the present. If any of these have a better net present value than the alternative of no restart, the existing stand should be restarted.

For example, suppose loblolly pine planted at a rate of 778 seedlings/ac (1,922/ha) on land with a site index of 60 (height, in feet, at base age 25) is sampled at age 3, and the number of seedlings surviving is only 300/ac. We also estimate, using the APA method developed by Matney and Hodges [13], that 53 seedlings/ac (131/ha) occupying an area of 12,500 ft^2 (1,161 m^2) are essentially open grown [the remaining 237 seedlings/ac (586/ha) occupy an area of 31,060 ft^2 (2,885 m^2)]. Hence the stand can be forecast to have

$$\frac{43,560}{31,060} \times 237 = 322 \quad \text{trees/ac} \quad (883/\text{ha}) ,$$

which then can be reduced by

$$\frac{12,500}{43,560} \times 100 = 28.7\%$$

to approximate the expected yield. The assumption is that we can ignore the yield of trees having large APAs. (A computer program for estimating the area occupied by open-grown and non-open-grown trees can be obtained by writing to Department of Forestry, P. 0. Drawer FR, Mississippi State, MS 39762.) For example, using a loblolly pine simulator developed by Matney and Sullivan [14] and modified for cutover sites, we can estimate yields after thinning for different product types (Table 18.7).

With a site-preparation and planting cost of $120/ac ($296/ha), a brush-control cost of $60/ac ($48/ha) at age 7, an interest rate of 13%, and stumpage prices of $17/cunit and $170/thousand Doyle bd ft, the net present value (NPV) of the stand with poor survival harvested at age 35 is —$98.81/ac (—$244.16/ha). At this interest rate, we certainly cannot afford to grow trees, but will replanting improve things? To answer this question, we must look at the NPV of a successfully replanted stand, recognizing that if the second planting fails we are in trouble.

So, assuming 80% survival and replanting at age 3 at a cost of $100/ac ($247/ha) with one additional thinning, the NPV is —$171.58/ac (—$423.98/ha). We must conclude in this case that because the NPV of the replanted stand is less than that of the original stand, we should not replant. Indeed, with these NPVs we would not have planted seedlings. We did not, however, include in this analysis taxes and other factors that may have considerable influence on forest-management decisions (again, see chapter 2).

18.6 Summary and Conclusions

Several survey methods suitable for collecting data to evaluate regeneration success have been discussed. Which one to use depends primarily on the type of information needed, but for most silvicultural and management decisions the methods that evaluate distribution as well as numbers of seedlings will be preferred. Figure 18.3 shows a typical flow chart for designing an evaluation procedure.

Table 18.7. Adjusted yields for different product types for a loblolly pine plantation with poor and better than average survival, estimated with a simulator developed by Matney and Sullivan [14].

	Standing volume after thinning			Volume thinned		
Age, years	Pulpwood, ft^3 (ib)	Chip & saw, Doyle bd ft	Veneer, Doyle bd ft	Pulpwood ft^3 (ib)	Chip & saw, Doyle bd ft	Veneer, Doyle bd ft
			Poor survival			
15	235	859	35			
20	98	911	514	110	675	489
25	79	985	1,697			
30	72	951	3,011			
35	65	1,018	3,840			
			Better than average survival			
15	821	595	0			
17	433	613	1	406	556	1
20	382	1,302	265			
23	329	1,658	735			
25	160	1,244	872	151	623	262
30	141	1,414	2,434			
35	124	1,531	3,606			

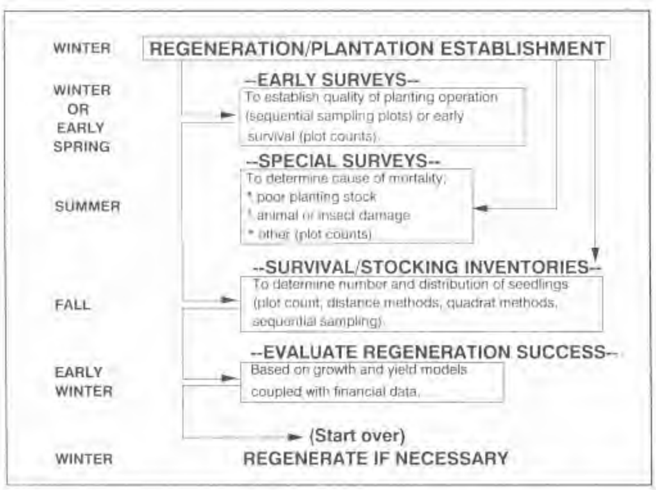

Figure 18.3. Sample time schedule and operations which may be involved in evaluating regeneration procedures and success. Methods for determining survival and stocking inventories are described in the text.

The decision as to minimum acceptable stocking should be influenced strongly by product objectives. Short rotations for products such as pulpwood will necessitate higher levels of stocking than will longer rotations for products such as sawlogs. The tendency in the past has been to establish arbitrarily a minimum number of surviving seedlings per unit area, but a better approach would be using growth and yield simulation coupled with financial analysis.

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