EVOLUTION OF SILVICULTURAL THINNING: FROM REJECTION TO TRANSCENDENCE

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Abstract—Our views on a main tool of forestry, silvicultural thinning, have changed greatly since the beginning of forestry over 200 years ago. At first, thinning was rejected as something unnatural and destructive. It was believed that the densest stands were the most productive and any thinning only detracted from maximum growth produced by nature. This philosophy was still dominant during the second stage when the "fathers" of forestry developed the practice of light thinning from below. It took another 100 years to acknowledge the benefit of a less "natural" medium to heavy thinning. During the last 70 years, the consensus has been that, within a wide range of densities, stand growth remains more or less constant. Even better results can be achieved when density increases with age. Heavy thinning at the beginning speeds up growth, whereas higher stocking at the end secures a larger final harvest. The last stage takes the trend of progressively lighter thinning to its logical conclusion: to control density by planting only the trees we intend to harvest at the end of rotation. Wood quality and stem form can be improved by pruning. Specific management recommendations are provided.

INTRODUCTION

Our attitude toward silvicultural thinning has evolved from total prohibition to the realization that thinning is not the best method to control stand density and maximize yield. Given that our views on thinning intensity have returned to the point where we started, this trend can be characterized as a revolution (the action of going round) rather than evolution. Several other concomitant trends are truly evolutionary. They include the increase in initial spacing of planted trees and a diminished enthusiasm for worshiping nature. Major stages of these trends are described below.

HISTORY OF THINNING

Initial Proscription

In the 18th century when forestry was systematized, forests in densely populated countries of Europe were badly depleted by irregular and usually illegal cutting of timber by local peasants. This kind of "thinning" instilled the belief that any thinning only detracts from the maximum growth produced by nature. At that time, thinning was considered as something unnatural and destructive, useful only to get a quick return at the expense of the final harvest. This belief was further supported by not only the popular veneration of nature but also by reasoning, both physical and ecological. That thinning could increase growth seemed to violate a basic law of nature: Nothing comes out of nothing. Equally convincing was an ecological consideration: A complete canopy intercepts more light and consequently should be more productive than a broken canopy. Forestry had not yet realized that thinning accelerates growth, and when foresters were in charge of forests, they opposed thinning (Fernow 1913).

Another manifestation of the preoccupation with full stocking was planting density. Traditionally, foresters tried to copy nature and planted as many seedlings as found in natural regeneration. As reported in Savill and others (1997, p. 160-161), in some parts of Germany, even the relatively intolerant Scotch pine is still planted at 10,000 to 18,000 trees/ha, which is "a considerable reduction from earlier practice." This tradition overlooks the critical difference between natural and planted regeneration–-us. Only few trees survive until maturity under natural conditions and almost all when we control intra-and interspecific competition.

Light Thinning

After securing forest protection, foresters recognized the economic advantage of harvesting suppressed trees after the remaining trees were cleared of lower and middle branches. This timid beginning of silvicultural thinning (called German or light thinning from below) is attributed to the "fathers" of forestry, Georg Ludwig Hartig and Heinrich von Cotta (Fernow 1913). Particularly influential was the publication of Hartig's "Instructions on the Evaluation of Forests" in 1795. Its third "General Rule" of forestry required keeping such a density that prevents vegetation on the forest floor (Fernow 1913, p.103). The instructions recommended periodic removal of suppressed, damaged, and undesirable trees when they could be sold profitably. At the same time, Hartig (1795, p. 17, translated by Hans Pretzsch) saw the harm done by high density and regretted "that there are unfortunately many foresters who do not thin forests but permit all stems to grow up together and refuse to deal with the excesses of abundance." Yet, he still sternly warned against ever breaking the canopy. To maintain the full closure, he would retain up to half of the crooked trees. These views had "the greatest influence upon the treatment of German forests between 1795 and 1914 (and even later)" (Kostler 1956, p.238).

Thinning to Increase Growth

In addition to his many distinguished hats, the great Danish statesman Christian Ditlev Frederik Viscount Reventlow was also a forestry prophet. On the basis of observations of tree growth in his vast estates, Reventlow realized that thinning actually stimulated stand growth. As a result, the total stand volume increases and does not diminish, as was presumed from a facile analogy with physical laws of conservation. Reventlow believed that frequent thinnings substantially reducing canopy closure would increase not only merchantable volume but total production and volume per unit area as

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well. To Reventlow's skeptical contemporaries, his view was equivalent to the possibility of having your cake and eating it, too. Outside Denmark, a brief summary of his results that appeared in 1811 (Mar:Moller 1954), and his book published in 1879 failed to change forestry practice.

It took 100 years after Reventlow's announcement of 1811 to acknowledge the benefit of medium to heavy thinning by forestry professionals. The decisive factor was the analysis of permanent plot data that replaced chance observations and heated arguments. Many plots, established in Germany in the second half of the 19^{th} century, produced first results at the beginning of the next century. Summarizing the results of 30 years of observations on 40 permanent sample plots established in Prussian beech stands, Schwappach (1911) showed that heavy thinning substantially increased the total volume growth. Scientists in other countries, including the United States, quickly arrived at similar results (Li 1923).

Thinning to Redistribute Growth

The enthusiasm brought by the possibility of increasing stand growth was short lived. In 1932, Wiedemann, Schwappach's successor in charge of the Prussian Forest Experiment Station, using longer 50-year-old observations of the same beech stands, demonstrated that, within a wide range of density, total wood production is almost independent from thinning intensity. An indistinct peak of total volume production occurring at a moderate density was documented by many researchers in Europe and the United States. The prevalent consensus at present is that thinning can redistribute volume growth from smaller to larger stems but cannot increase its amount: "As long as the site is fully occupied (trees making their full use of available resources), the species will produce the same amount of wood per year at various densities. Whether there are many small trees or fewer large trees, a similar wood volume is produced" (Spurr and Barnes 1980, p. 376). Graphically, this conviction is depicted by Langsaeter's curve (shown in Daniel and others 1979, p. 318).

In this country, the optimal range of density is defined quantitatively, usually in terms of basal area per unit area. To maximize stand volume in even-aged loblolly pine (*Pinus taeda* L.) stands on good sites, many authors (Chapman 1953, Schultz 1997, Wahlenberg 1960) recommend keeping basal area between 28 m^2/ha (thinning density) and 18 m^2/ha (residual density). Lately, stand density index (Reineke 1933) has become popular for specifying the optimal range of density. Dean and Chang (2002) recommend growing loblolly pine between indices of 610 and 390. Doruska and Nolen's (1999) estimates of the range are 560 and 390. Similar values (540 and 390) are used by Williams (1994).

Thinning to Variable Density

These recommendations would be sufficient for maximizing wood production if we have to maintain the same average stand density over the rotation. But nobody has proved that keeping density at 15 years the same as at 35 years would maximize final and total harvest. It may be possible to increase forest production by varying current density during the lifetime of a stand. Although maintaining a fixed level of average (and residual) density is still a common practice, some forest scientists perceive the advantage of density that increases with age. Already Wiedemann (1937) and later Assmann and Franz (1965) advocated the so called "staggered thinning". Its advantages are twofold: fast growth at the beginning when density is low and high final yield and income secured by full stocking at the end.

Similar observations were made by Burton (1980, p.22) in the United States. He found that the best sawtimber yield of loblolly pine was produced by "initial heavy thinning from below, on good sides, to a basal area of 70 square feet per acre (16 m^2/ha) at age 20 and then increasing the residual stand density by 5-square-foot (1.15 m^2/ha) steps." In practice we do not keep average density constant all the time: To accumulate more volume for final harvest, usually we do not thin stands in the last 5 to 10 years. Instead of keeping a fixed level, during this final period we let density increase.

PROPOSED SYSTEM

The proposed system develops further the benefit of progressively higher density and brings the idea of variable density to its final form. Although the system has been developed and tested for loblolly pine, it is applicable to even-aged stands of any species.

A Rule to Maximize Final Yield

For a given site, stand volume in general and final harvest in particular increase with stand density and average tree size. Maximum density maximizes volume growth at a given moment, but it decreases average tree size and, as a result, may not be optimal in the long run. On the other hand, the maximization of the second component of the harvest, average tree size, requires maintaining the lowest density. To minimize the negative side of density (small size) and maximize its positive side (maximum volume of trees with a given size), we need to find an optimal trajectory of density rather than a single optimal value or a range. The trajectory should start with a low density at the beginning of tree life (to increase tree size) and end with a density high enough to assure maximum final harvest or income. This rule for maximizing final yield differs from the views held in the past: Optimal density is not in the middle and not at the highest density; it is at the low extreme at the beginning and at the high density at the end.

Minimax Strategy

The rule is clear about the initial and harvest densities but not about the intermediate values of the optimal density trajectory. Ideally, density should be minimal until harvest and then jump to the maximum. Since density does not increase instantly, it seems that we have to find some equation describing a gradually increasing trajectory of basal area or stand density index. A simpler description of the optimal trajectory can be cast in terms of the number of trees per unit area—Keep it constant. When the number is constant, stand density increases with age due to diameter growth. The number should be the minimum that assures the density sufficient to maximize yield (or income) by harvest time. At the beginning, the number secures the minimum density and, as a result, the fast diameter growth.

Such a prescription is called the minimum number-maximum yield (minimax) strategy. Albeit unknown in forestry, it is not new. For millennia, farmers have grown only the plants (sometimes after the initial thinning of seedlings) they intend to harvest. In addition to the chief advantage, maximum final volume, this strategy has several other advantages such as saving on planting and thinning. This strategy dealing with number of trees and their yield is not to be confused with the minimax in game theory, which operates with different concepts.

Disadvantages of Minimax

The minimax strategy may maximize final yield in theory but in practice it would not work as is for the following reasons:

1. Interspecific competition—at the beginning, minimax requires less than 10 percent of land for trees, which provides large savings on tree planting and tending. Yet, this feature is a mixed blessing if the remaining land is left unattended. Competing vegetation, especially hardwoods, would kill most of the pines and reduce the growth of the remaining survivors.
2. Establishment mortality—even well spaced trees suffer mortality, especially during the establishment period. Losing 20 to 30 percent of trees does not have much effect on regular plantations but would hurt those started with a minimum number of trees.
3. The lack of selection—in regular plantations the excessive number of trees allows the forester to select the better ones. Planting the minimal number removes this important method of stand improvement.
4. Poor quality of wood—the initial low stand density would diminish wood quality so that trees could be sold only for pulpwood.

To realize the potential of the minimax strategy and turn it into a practical management system, it is proposed to combine forestry with agriculture and use several silvicultural techniques, including cluster planting and pruning.

Diversifying Land Use: Agroforestry

Instead of struggling with the competing vegetation, we can put to agricultural use the portion of land unutilized by pines until they close their crowns. Thus, minimax leads naturally to diversified land use—agroforestry. It is a natural extension of forestry; optimal forestry is agroforestry. The space between pine rows can be used to grow forage or any crop (wheat, oats, soybeans) that does not compete with trees for light. When trees reach the cow-resistant height (3 to 4 m), grazing can be permitted. Combining the two most common kinds of land management, forestry and agriculture, is attractive for a variety of ecological, economic, and personal reasons. Root systems of established trees are deeper than those of agricultural species. This fact minimizes competition for soil nutrients and moisture, and allows for fuller land utilization. The following benefits of agroforestry are compatible; indeed, they complement each other: (1) for trees—minimal cost of establishment; control of undesirable vegetation; natural and artificial fertilization, which come as byproducts of agricultural use; stand density that maximizes growth of trees (low at the beginning and high at the end); accessibility for pruning and harvesting; reduced damage from ice, root rot, and wildfire; (2) for agricultural crops and cattle—land for cultivation or grazing; shade for animals; wind shelter for cattle and crops. The microclimate of agroforests is favorable to both plants and animals. It is characterized by higher soil moisture, humidity, and night-time carbon dioxide levels and lower evaporation that result in reduced respiration rates; (3) for the land—when tree rows are planted along the contour, erosion is minimized. Cattle manure increases soil fertility and activates many beneficial processes that are suppressed in dense forest monocultures. By definition, agroforests have more plant species then either of the components. Reflecting this fact, they are inhabited by a greater number of animals; and (4) for landowners—increased utilization of the land potential and the mutualistic nature of the agricultural and forest uses mean higher income as compared with growing trees and agricultural crops separately. Risk is spread over a number of crops, and cash flow is more stable. While the returns from the forestry component will materialize 20 to 25 years after the planting, the agricultural components will provide most of their returns during the initial period. Agroforestry also fits the human life cycle. As individuals become older, they prefer less strenuous activities such as timber management. If a farmer switches to agroforestry in his middle years, then this transition will occur naturally.

Initial Spacing for Density Control

Minimax avoids thinning altogether (except, the initial cluster thinning) and controls density by planting only the trees to be harvested at the end of rotation. The main advantage of this approach is the maximum income from final harvest. In even-aged stands, this harvest always brings the larger part of the total income. With the declining market for small timber, the part of final harvest approaches the whole 100 percent.

Cluster planting—Some of the minimax disadvantages can be corrected by planting trees in clusters rather than singly. Each cluster consists of 4 seedlings planted at the corners of a square with sides of 30 cm. All but one tree per cluster is to be thinned by age 5. Along with other features of the proposed system, cluster planting was tested on an agroforestry study established by our school in Hope, AR, during 1997-1998 (Zeide 1999, 2003). Clusters provide the possibility of selecting better trees, eliminate (or at least drastically reduce) the disruption of stand structure caused by mortality and assure the needed number of crop trees.

Pruning

Traditionally, foresters improved wood quality by keeping high stand density. Unfortunately, such density kills many trees and slows the growth of the rest. Pruning is a better way to improve stem form and wood quality than choking trees with density. Pruning improves wood quality physically by cutting off branches and physiologically by removing the apical meristem (which stimulates the production of juvenile wood) with the limbs and forcing trees to grow taller, which moves the crown apical meristems further from the lower bole. Pruning also makes the pruned portion less tapered, though it increases the size of knots above the pruned area. Two prunings are recommended. The first clears 50 percent of the bole when trees reach the height of about 5.5 m. The second pruning, done when trees are 8.6 m high, clears 60 percent of the bole (one sawlog of 5.2 m).

Growth Projection

In order to predict stand dynamics, a set of models has been developed to describe growth processes (Zeide 1993, 2002, 2004a, 2004b, 2005). The core of these models is a proposition that, for any even-aged stand, three variables (average tree size, y, age, t, and current density, s) are necessary and sufficient to predict the increment of the size, y'. These variables are convenient proxies of all growth factors. Size and age stand for two groups of density-independent factors, those that boost growth and those that impede it. Stand density index represents all density-dependent forces. This proposition is expressed as an equation consisting of three modules driven by the predicting variables:

$$y'(y,s,t) = ky^p e^{-(t/g+s/m)} \quad (1)$$

where

k = a measure of site quality for a given species

p = the rate of unrestrained growth

g = the rate of various factors slowing growth, primarily aging

m = the maximum stand density index

Each parameter and the form of the modules are ecologically meaningful. Parameter p is equal to one third of fractal dimension (sponge dimension) of the average tree and could be measured directly in the field. Parameter g is a function of p and the age of the inflection point, $t_\$$, of a given variable: $g = -t_\$/ln(1-p)$. It is related to the natural longevity of a species, that is, the maximum of age. It appears that g and m serve to normalize the corresponding variables. At least for diameter, the age of inflection, $t_\$$, can be measured on a tree cross-section (it is the number of rings from the pith to the largest ring). Another fractal dimension, called the sieve dimension, which is obtained from measuring a two-dimensional projection of tree crown, is the power to which diameter is raised in the stand density index that is used to predict growth (as opposed to mortality). Both dimensions describe the spatial structure of trees, or, more specifically, pattern of foliage distribution, which could be determined instantly. Besides theoretical interest, the link between the spatial and temporal (growth) characteristics (parameter p) can expedite time-consuming studies of stand dynamics.

Data

Model parameters were computed using the data from several sets of permanent plots, including the Monticello thinning and pruning study, which is the longest active and, as far as density is concerned, the most diverse thinning and pruning study of loblolly pine. The 45 plots, currently 48 years old, were measured 11 times and thinned 7 times to the target basal areas of 20.7, 16.1, 11.5, and an unusually low 6.9 m^2/ha. The variation in stand density was further enhanced by 3 severe ice storms that occurred at ages 16, 21, and 36. The long-term observations of loblolly pine plantations maintained by the Loblolly Pine Growth and Yield Research Cooperative at Virginia Polytechnic Institute and State University were also used in this investigation, specifically for mortality estimations. This set is described in Burkhart and others (1985). The initial values for modeling were taken from the agroforestry study in Hope. The applicability of the developed models was also tested using data for teak (*Tectonia grandis* L.f.) from Kerala, India, and for Norway spruce [*Picea abies* (L.) Karst.] and European beech (*Fagus sylvatica* L.) from the oldest Bavarian plots that have been remeasured for over 100 years.

Economic Analysis

Economic analysis of the proposed system is based on the following assumptions: An agroforest is established in an existing pasture, which belongs to the landowner; the initial annual net returns from the portion of land used by agriculture are $124/ha (Husak and Grado 2002), the portion of land for agricultural use decreases as trees become larger, the interest rate is 6 percent, the stumpage price is $36 per ton for sawlogs and $8 for pulpwood, post-establishment mortality and other hazards reduce income by 10 percent, and several others. This information is used to compute the equal annual income, which combines all costs and returns into a single annual sum. It is equivalent to all cash flows spread uniformly over the rotation period. The results of economic analysis show that on poor sites with site indices of less than 17, agroforestry is unprofitable (table 1). Modifications of interest rates and values of pruned sawlogs increase income but do not change the optimal rotation age and number of trees/ha. Income is very sensitive to site quality and on good sites, site index > 20, it doubles sustainable returns as compared with regular forestry or agriculture practiced separately.

The described system makes it possible not only to increase financial returns but to maximize them as a result of the following activities: optimization of stand density throughout the rotation, optimization of rotation period, diversification of land use by growing compatible species, improving quality of merchantable wood by cluster planting and pruning, reduction of expenses on planting and thinning, minimization of root rot, insect infestation, and other risks associated with high density, which would be maintained only during a relatively short period before harvest, and growing sturdy well-spaced trees with symmetrical crowns which would reduce ice damage and other hazards.

Thinning Returns

Since thinning has been an integral part of forest management, some foresters consider the loss of income from thinning as a serious shortcoming of minimax. This impression seems reasonable. However, economically it makes little sense because benefits of a faster growth rate and agricultural income outweigh the financial gain from thinning. To settle

Table 1—Characteristics of agroforests at the age of maximum returns (equal annual income), by site index (base age is 25 years). N is number of trees/ha at that age, D is average tree diameter in cms, weights are in ton/ha, and income is in $/ha

				Weight				Returns			Equal annual income		
Site index	Age	N	D	Top	Pulp	Sawlog	Total	Pulp	Sawlog	Total	Field	Stand	Total
15	33	173	29.5	0.5	15	91	107	119	3,610	3,731	87	19	106
17	29	247	30.5	0.8	17	154	172	135	6,121	6,254	78	55	132
18	27	346	30.5	1.1	23	235	259	184	9,318	9,503	66	104	170
20	25	420	30.5	1.3	29	295	325	233	11,671	11,903	60	158	218
21	23	445	30.7	1.4	28	331	361	228	13,106	13,334	58	214	272

this question, the model incorporating the equations and assumptions described above was run for site index 20.4 (base age is 25 years), which is the actual average index of the Monticello plots. Without thinning, maximum annual income/ha of $237 can be obtained by planting 400 trees and harvesting them at age 24.

If at the age of 15 half of these trees are thinned and sold as pulpwood while the remaining 200 trees are grown for sawlogs, maximum income at age 25 drops to $170. This number, however, underestimates the income, because when half of the trees are thinned, the optimal planting number is 700 and not 400 trees/ha. Running the model for this number, half of which is thinned for pulpwood and the rest kept until 26 years, raises the income to the maximum of $177, which is 25 percent smaller than the minimax returns of $237. These calculations show empirically that thinning does not pay, and that the best strategy is to grow, after the initial thinning of clusters, only the trees intended for final harvest.

DISCUSSION

After centuries of striving to maximize forest productivity, we have arrived at the original recommendation regarding thinning: Do not thin forest stands. This does not mean that we are just walking in circles; many other things have changed. Some of these changes are summarized in table 2.

Respect of Nature Rather than Worship

Progress in thinning and planting has been achieved since we stopped imitating the growth of undisturbed stands. In forestry, the reverence of nature has been misplaced and counterproductive, because it neglected our knowledge and ability to improve growth on a sustainable basis. Our planes fly like birds and even better, but they do not flap their wings. Similarly, our way to grow trees need not copy what is going on in the wild. Because we care for trees, they grow and survive much better than those tended by nature, which cares for many other creatures that kill the trees we plant. The rejection of the "aping" of nature does not mean that our work destroys the natural potential and diversity (Zeide 2001). Agroforests are definitely more diverse and productive than natural monocultures of pine or soybeans.

Table 2—Evolution of silvicultural thinning. The arrow indicates a gradual transition from high to low numbers of trees planted per hectare

		Technical implementations	
Period	Conceptual development	Thinning intensity	Planted number
Prior 1795	Thinning decreases growth and volume	No thinning	> 20,000
1795-1911		Light	
1911-1932	Thinning increases growth and volume	Medium-heavy	
1932-present	Thinning redistributes growth	Medium-heavy	
1937-present		Decreasing	
2005-	Initial spacing as density control	No thinning	250-450

What Is Ahead?

Could the exposed trends shed some light on the future development of forestry? One thing we can learn is that not all trends are continuous. Some drastic changes could occur. The second lesson is that our method is to actively modify growth processes and conditions, rather than to copy those of undisturbed forests. Third is that, while many things have changed, some remain constant. One of these is the tug of war between quantity and quality of wood. The history of forestry can be presented as various tradeoffs between these opposing characteristics.

This dilemma between quantity and quality of wood may be resolved soon. We used to think that the abundance of light was good for quantity but bad for quality of wood. If so, the conflict is unavoidable. Actually, the situation is more promising. Over 50 years ago, it was discovered that, as far as trees are concerned, what we call light consists of two distinct components—energy to grow and the signal to modify the shape. The signal, which is the ratio of the radiation intensity in the red part of the spectrum (wavelengths between 650 and 680 nm) to that in the far-red (between 710 and 740 nm), shortens trees and plants in general (Smith 2000) and makes them branchy. Natural shading connects these components so that deficiency of energy comes together with improved tree form. But genetic engineering is capable of decoupling this connection. Disabling the receptors of the signal (phytochromes) removes the inhibition of stem elongation, decreases allocation of photosynthates to seed production, and enhances apical dominance (Smith 2000). In other words, we can get trees growing faster than open-grown trees but as slender as forest trees. Although a dream today, this possibility could transform the forestry of tomorrow as nothing before.

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