2

Silviculture

Challenging Traditions

The discipline of silviculture is the management and study of forests to produce desired attributes and products. Silviculture has strong traditions that have been developed, articulated, and refined over several centuries (chap. 1). Throughout this time, the objective of most landowners, and therefore of most silvicultural activities, has been the efficient production of wood for timber or other wood-based commodities. Accordingly, silviculturists have successfully focused on developing practices to efficiently regenerate forests and increase wood production and quality.

Although there has been, and continues to be, a strong emphasis on wood production in silviculture, the discipline should not be considered a homogeneous field. The management of seminatural woodlands and protection forests are also aspects of silviculture. Throughout history, silvicultural principles have been used to manage forests to promote wildlife habitats, to ensure hunting opportunities, to provide reliable sources of clean water, to protect settlements from snow or rock avalanches, and to establish and maintain tranquil forest settings.

Silvicultural practices, regardless of management objective, aim to control the establishment, composition, structure, growth, and role of trees within managed forests. Preferred tree species are established through natural regeneration, direct seeding, or planting. Composition refers to the variety of tree species and their relative abundance. Structure comprises the internal characteristics of forests including tree crowns, vigor, diameter and height distributions, the abundance and types of dead trees (snags), the presence of wood on the ground, and understory vegetation. Silviculturists manage tree growth and quality by manipulating tree species composition and density, by removing other competing vegetation, and by improving site productivity. They manage habitats by retaining or promoting specific forest structures such as snags and old large trees.

Silvicultural activities are implemented through a series of individual practices (e.g., site preparation, promoting natural regeneration, planting, fertilization, thinning, and final harvest of individual trees or stands based on diameter or age; see Hawley and Smith 1972; Daniel et al. 1979; Burschel and Huss 1997; Smith et al. 1997; Fujimori 2001; Nyland 2002) that promote the desired species and structural characteristics within and among managed areas in a forested landscape. Individual silvicultural practices are integrated into a silvicultural system, which can be viewed as a larger program of activities aimed at achieving desired tree composition and growth objectives (see chap. 1). Probably the single greatest defining characteristic of the discipline of silviculture is the concept of silvicultural systems and their application in the management of forests (Troup 1928; Matthews 1989; Mantel 1990). While individual practices have changed over the years based on better understanding of their impacts or new technologies, the suite of even- and uneven-aged silvicultural systems formalized in central Europe in the nineteenth century are still being applied today in forested regions throughout the world with surprisingly few modifications. As a result, silviculture across the globe has a common origin. The basic structure and principles of the discipline are often considered to be independent of local conditions (Hawley and Smith 1972; Burschel and Huss 1997; Fujimori 2001; Nyland 2002).

The discipline of silviculture can be best understood by examining five core principles that have formed the basic foundation of silvicultural thinking, study, and practice: (1) a strong focus on trees to the exclusion of other plants, animals, and ecosystem processes, where these are not relevant to the task of growing trees; (2) conceptualizing stands of trees as uniform management units; (3) applying an agricultural approach to silvicultural research, especially the search for best treatments that emphasize uniform tree species composition and structure; (4) the scale-independent view of silvicultural practices; and (5) a strong desire for predictable outcomes.

The core principles are focused on the most dominant objective of silviculture to optimize the quantity and quality of wood products. They have guided silvicultural practice globally and remain a strong influence in contemporary silvicultural thinking and practice. While exceptions clearly exist, we believe that silviculture as a discipline is strongly influenced by entrained thinking and tradition, and that insights can be gained by all silviculturists in reviewing the set of core principles in the context of their influence on addressing present-day issues.

A Dominant Focus on Trees

The development of natural sciences, including silviculture in the seventeenth and eighteenth centuries, reflected the writings and beliefs about nature of the principal philosophers and scientists of the time (e.g., Descartes, Newton, and Kant). Rational thinking and Newtonian mathematics implied that nature, and therefore forests, were driven by universal laws. It was considered man's obligation to bring order to nature. This rational view of the natural world was heavily influenced by Newtonian mathematics, which relied on simplification and linear relationships (Hampe 2003). While it is unlikely that many silviculturists read Newton's writings, the philosophical view of nature still influenced their work. For example, straight lines or sharp edges were perceived as superior by Newton, likely influencing the linearity and regularity of early silvicultural operations, especially those in Europe aimed at reforesting highly degraded forests to mitigate the wood famine (see chap. 1).

Early silviculturists managing for wood production believed they were enhancing the ultimate goal of nature by taming nature; that is, transforming degraded woodlands or natural forests into more orderly arrangements of desired tree species with balanced age classes (see normal forest discussion in chap. 1). To tame nature, silviculturists developed a suite of practices that centered on controlling biotic and abiotic conditions to reliably enhance the performance of the tree species with the most desirable growth and wood properties (for a more thorough discussion of these practices, consult silvicultural textbooks).

Most early silvicultural practices aimed to make forests conform to this worldview. For example, unproductive sites and dead trees were seen as a waste and thus were restored to productivity by drainage or fertilization or removed in harvesting operations, respectively. Despite many subsequent changes, most notably in our ecological understanding of forest functions, this worldview remains pervasive in contemporary silvicultural thinking and practice. Especially in plantation management but also, in different dimensions and to a different degree, in management of seminatural woodlands, the "obligation to bring order" combined with economic efficiency resulted in uniformity of forest practices and simplified forest structures. The desire for order and simplification is even evident in intensively managed present-day, uneven-aged forests.

Taming Nature: The philosophical view that the "messy" natural forest needs to be transformed into a forest that is improved and superior has a long history in silviculture. Expressions in French (*il faut éduquer la forêt*) and German (*Walderziehung*) implied that the natural forest needed to be "trained" or "educated." This translated into simplifying forest structures and uniform conditions. The concept that managed forests are better than natural forests in achieving ownership objectives is still evident in contemporary silvicultural thinking: "in silviculture, natural processes are deliberately guided to produce forests that are more useful than those of nature, and to do so in less time" (Smith et al. 1997, 5).

The most visual evidence of the silvicultural emphasis on regularity and evenness is the control of tree density and spacing in managed even- and uneven-aged forests. In plantation management, trees are planted in square or rectangular spatial patterns. In natural stands with dense natural regeneration, regular tree spacing is achieved through thinning. Often, the first thinning entry is focused on providing regular, optimal growing conditions, rather than a direct economic return. It is thus labeled precommercial thinning or spacing because trees are usually too small to be sold profitably. Commercial thinning takes place in older natural or managed stands where the cut trees can be sold. In managed uneven-aged forests the number of trees allowed in various diameter classes and the size at which the largest trees are cut is controlled to promote maximum growth onto the selected trees. The major aim of the control of tree density and spacing in managed even- and uneven-aged forests is to focus the full growth potential of a site to a limited number of desired trees and thus maximize economic gain.

In efforts to control and improve on nature, genetic improvement programs were developed to select seeds for regeneration from parent trees with superior growth and wood quality. Plantations in New Zealand, Chile, and Argentina that were established with an extremely narrow focus on specific wood products provide the most remarkable examples of impacts of silvicultural practices aimed at maximizing wood production. Displaying a striking difference from native forests, monospecific plantations in these regions are even-aged, with evenly spaced trees of similar size and form. Furthermore, these plantations are typically composed of tree species that are not native to the area.

All practices described above, to lesser and greater degrees, aim to develop an ideal forest that is composed mostly (or preferably only) of vigorously growing, healthy trees of high wood quality, most commonly in single-species even-aged stands, but also in mixed-species or uneven-aged stands. Desired trees are now often referred to as "crop trees," a term that implies trees can be managed like crops in an agricultural field (Cotta 1816).

The emphasis on controlling species composition and spacing to enhance tree productivity and value remains an influential feature in the discipline of silviculture, as encapsulated in a quote from Smith et al. (1997, 4): "silviculture for timber production is the most intricate kind because the species and quality of trees are of greater concern than they would be with other forest uses." This view has many advantages, one of them being that the successes of silvicultural practices were quantifiable by measuring the quantity and quality of trees.

The management goal of timber production and the associated emphasis on trees also provides a clear picture of what a successful, well-managed forest should look like, one that efficiently provides homogeneous, high-quality timber. Consequently, regions that practiced intensive silviculture following this approach gained reputations as examples of good forestry and became the subject of many field trips and excursions. For example, the intensively managed Scandinavian or New Zealand plantations have long been considered showcases of successful industrialized forestry operations. Alternatively, forests managed intensively by uneven-aged single-tree selection (e.g., *jardinage* or *Plenterwald*) (Matthews 1989), and more recently by "close-to-nature" approaches, have drawn visitors as showcases of successful silviculture in central Europe (Jakobsen 2001; Pommerening and Murphy 2004).

Because trees are long-lived organisms, silviculturists have had a longer-standing familiarity with the concept of sustained yield and sustainability than have experts in most other disciplines (Peng 2000). The focus of silviculturists on trees, however, also limited the scope of their interest in sustainability (Morgenstern 2007). The sustainability principle can be traced back to von Carlowitz (1713), who was interested in ensuring a continuously high wood supply for mining needs. Of course, in some areas in central Europe, sustainability of hunting opportunities for landowning nobility was another early concern to silviculturists. The vast majority of silviculturists, however, have come to equate the sustainability of forests with the sustained yield of timber (Morgenstern 2007). One inherent feature of such a strong management focus on trees was the acquired belief that other characteristics of the forest ecosystem would benefit or at least not be harmed by such management activities. This is reflected in the statement that "what is good for the trees is good for the forest." The implication was that forests managed for timber production

Sustained Yield and Sustainability: Trees and forests are renewable resources, so it is appropriate to discuss sustainability, which is the ability to maintain something undiminished over time (Lélé and Norgaard 1996). Sustained yield assumes that any tree species or community of tree species produce each year a harvestable surplus that can be harvested so as to maintain the capital and the productivity of the forest (Larkin 1977). The meaning of sustained yield, as applied to the management of trees for timber production or deer for hunting, and the concept of sustainability of forest ecosystems are distinct though related concepts (Hilborn et al. 1995). Sustainability encompasses a wider array of resources and values and has ecological, economic, and social dimensions (Levin 1993).

would also automatically provide all other forest values and functions. This continued to be a strongly held belief until recently (Pretzsch 2005).

Because silviculturists have tended to view forest ecosystems through a tree-focused lens, other components of forest ecosystems were often considered only in terms of their impact on individual tree survival and growth. For example, herbs, shrubs, and trees other than the desired tree species were not managed in relation to their potential contributions to nutrient cycling (Attiwill and Adams 1993) or wildlife habitat (Hunter 1990). Instead, the major interest of silviculture in dealing with these ecosystem components was to limit their competition with crop trees (Wagner et al. 2006). Especially in plantation management, the focal point of silvicultural attention on other forest plants was their reduction or elimination (Walstad and Kuch 1987; Thompson and Pitt 2003; Wagner 2005). Silviculturists have generally evaluated ecosystem processes only in the context of their management goals. For example, interest in mycorrhizae fungi was focused on the potential beneficial effects of the fungi to seedling establishment and tree growth. Whether harvesting altered fungal communities or how the removal of competing vegetation impacted fungi and subsequent ecosystem function generally received little or no attention by silviculturists. With the wider range of management objectives, especially on public forests, the tree-focused nature of silviculture is undergoing a recent change (see examples in chap. 4).

Natural disturbance agents in forests were also viewed and managed in the context of their impact on tree and stand productivity. Decay fungi and insects were seen as damaging agents and discussed under the topic of pest control in silviculture classes and writings. Until recently (see chap. 4), disturbances such as fire or windthrow were mainly assessed in terms of their damage to trees and stands rather than as relates to their role in succession and ecosystem function. Unplanned disturbances were often labeled as catastrophes, and considerable silvicultural efforts were aimed at preventing or minimizing impacts of disturbance to ensure a predictable high level of tree and stand growth.

The idiom "can't see the forest for the trees" implies an excessive concern with detail resulting in a lack of understanding of the larger situation. As we learn more about the complexity of forest ecosystems (see chap. 3), we'll see that the idiom can be applied more literally to characterize the discrepancy between the emphasis on trees by traditional silviculture and our current understanding of how much more there is to a forest than just its trees.

Management of Stands as Uniform Entities

As silviculture evolved into a well-established discipline, the notion that forests should be managed on a stand-by-stand basis emerged as a key concept (Smith et al. 1997; Helms 1998). A stand is the most basic unit of management in forestry, consisting of a contiguous group of trees sufficiently uniform in age-class distribution, composition, and structure, and growing on a site of sufficiently uniform quality to be a distinguishable unit (Helms 1998). Stand management has resulted in efficient planning and inventory procedures, and the prevalence of managing homogeneous units has considerably influenced silvicultural thinking and views of forest ecosystems.

The delineation of stands in unmanaged forests is determined by landscape topography and prior disturbance events. Disturbances as determinants of stand size and boundaries deserve special attention. First, disturbances are fundamental to the development of structure and composition (attributes that help identify a stand) and maintenance of forest health and productivity (Oliver 1981; Attiwill 1994). Second, regional natural disturbance regimes have frequently been used to justify stand sizes and harvesting patterns. In most regions, however, natural disturbances in forests vary spatially and temporally from frequent small-scale, low-intensity, gap-forming disturbances operating at the level of individual trees to larger-scale, high-intensity events that affect large areas (Spies et al. 1990; Frelich 2002; Johnson and Miyanishi 2007). Thus, while both small- and large-scale disturbances are common in many forests, identifiable stands result mainly from medium- to large-scale disturbance events such as fires, windthrow, or severe insect infestations that kill most trees and result in relatively uniform regrowth. The preoccupation with delineating the external boundaries of stands based on large-scale mortality events allowed silviculturists to overlook small-scale within-stand variability as an alternative means of characterizing stands.

In regions where silvicultural management started with regenerating degraded areas or harvesting of natural forests, stands were typically

Figure 2.1. Example of a forest ownership with stands of Norway spruce and European beech in Sauerland, Germany. Note that stands are of small size and stand boundaries are obvious. Picture credit: Irene Breil.

delineated by logistical constraints. Harvest unit layout usually reflected concentrations of trees that were of greatest interest to loggers and topographic conditions. Stand size could vary considerably depending on physical, social, and historical constraints. The size and shape of the area harvested was often determined by the requirements of logging equipment or property boundaries. More recently, government regulations in most jurisdictions have put some limits on the size of harvesting units, which adds another element to how stands are delimited. In many regions of the world, stand boundaries were established centuries ago and subsequent silvicultural practices have ensured easy identification of the individual stands in the landscape (fig. 2.1).

Management intensity, ownership, and land tenure pattern also influence stand size. The size of individual stands can be quite small in the intensively managed, privately owned boreal forests of Finland (typically ranging from 0.5 hectare to 50 hectares) but are much larger in the more extensively managed publicly owned boreal forests of Canada and Russia (one hundred to several thousand hectares). Stand sizes in areas with longer management history tend to be smaller, reflecting early logging constraints and historical ownership patterns. For example, all private forestland in Croatia and Poland is in parcels of less than 5 hectares (Food and Agriculture Organization 1997) compared to 10 to 11 hectares average stand size on industrial, public, and tribal lands in Minnesota, United States (Puettmann and Ek 1999), and approximately 22 hectares on land owned by the forest industry in the Pacific Northwest of the United States (Briggs and Trobaugh 2001).

Probably the most influential aspect of stand management on silvicultural thinking is the traditional use by silviculturists of tree-based stand descriptors such as stems per hectare; tree diameter and height; current, periodic, or mean annual increment; basal area; merchantable or total volume; diameter distributions; and the "q-factor." Most of these descriptors are based on the assumption of underlying normal distribution, with one exception. The q-factor has a special place in silvicultural history and has been used to prescribe the desired diameter distribution of stands managed by the selection system (see chap. 1). The q-factor, first proposed by the French forester de Liocourt (1898), is an indicator of the ratio of the number of large trees to the number of small trees in a stand. Mathematically, it is reflected in the steepness of the negative exponential (reverse J-shaped) diameter distribution common to uneven-aged stands (see also figs. 5.4 and 5.6).

Stand Descriptors: Current annual increment is the amount of wood that stands add in any given year, whereas periodic annual increment is for some fixed period of time, usually five or ten years. Mean annual increment is the average amount of wood accumulated each year over the full life of a stand. This is a key value for determining a sustainable harvest level. Basal area per unit of land (square meters per hectare) is a measure of the cross-sectional area of tree trunks in a stand. It is easily measured using a prism and is a common means to describe stands. Total volume is the gross wood/stem volume of all trees in a stand (cubic meters per hectare), whereas merchantable volume includes only tree stems above a minimum size threshold.

Descriptors are usually averaged over the whole area of a managed stand. These averages are commonly used to describe stand structures and for planning timber management activities. Obviously, basing decisions on average stand conditions implies that stands are sufficiently homogeneous to be properly represented by an average value. Similar assumptions of homogeneity within stands are also inherent in stand descriptors that describe growing conditions. For example, the growth potential of a stand is frequently represented by the site index of the desirable tree species. Site index is a common, useful, and widely used measure in silviculture. It is also an example of the deeply entrenched focus on homogeneous stands. Site index utilizes trees as a bio-indicator of the potential productivity of a site and requires those trees to have grown without overtopping or any significant reduction of height growth. This limits its utility to uniform even-aged, single-species stands, and its use may thus implicitly encourage uniform stand management practices.

Site Index: The average height of the dominant and codominant trees at a specified age (SI_{50} = height at age fifty). Tree age is often determined 1.3 meters above ground level, at "breast height." Site index is a tree-centered quantitative metric that is used to express site productivity. It is based on the assertion that height growth is independent of crowding and thus reflects inherent site conditions. Since tree species have different growing requirements, the site index metric is species specific. Individual trees selected to determine site index are assumed to have grown without ever being overtopped by other trees.

The focus on average stand descriptors with their inherent assumption of homogeneity has also become the standard method of describing silvicultural practices. Individual prescriptions for silvicultural practices like planting (or thinning) propose a certain number of stems per hectare to be planted (or retained in a thinning) within an allowable deviation, typically limited in contracts to 5 or 10 percent. Prescribed densities are used to calculate desired distance between trees based on square or triangular arrangements. These inter-tree distances are then evenly applied throughout the stand.

The notion that all areas within a stand are similar, or at least similar enough to be represented by a single number, worked well in managed even- and uneven-aged stands, such as the most intensively managed plantations or selection systems forests. At a broader level, the traditional use of average stand descriptors has trained silviculturists to think and view forest ecosystems in terms of uniform conditions that can be easily summarized by use of an average descriptor. On the other hand, the variability often associated with dynamic ecological systems like forests did not receive the same attention.

The desire to fit forest management into the industrial efficiency paradigm cannot be underestimated in its influence in promoting the stand concept and within-stand uniformity. Especially with the onset of larger mechanized machinery, silvicultural prescriptions needed to be designed to take full advantage of industrialized tools and methodologies. For example, the types of equipment used in harvesting operations often dictate minimum stand sizes for cost-effective operations. Maximum stand size is also limited by logistical constraints as the area that "can feasibly be treated in a relatively uniform manner" (Tappeiner et al. 2007, 34).

As sawmills became increasingly mechanized and streamlined, they typically limited their operation to a few selected tree species and more recently even to a narrow range of tree dimensions. This development pushed silviculturists to plant monocultures of desired tree species for efficient management. For example, planting monocultures avoids the cost of sorting logs by species to supply different sawmills. At the same time, it became more important to produce consistent log sizes and qualities, which required more uniform growing conditions within stands.

Stand-based management has gained worldwide acceptance and usage in forestry for planning and implementing silvicultural prescriptions and practices (e.g., Smith et al. 1997; Fujimori 2001; Röhrig et al. 2006). It has proved quite successful at achieving the goal of increased management efficiency and timber productivity. The stand concept, which is institutionalized as desired or good forestry practice, provides an example of how management practices that developed in response to economic and logistical constraints resulted in further homogenizing conditions within—by definition—already homogeneous stands.

Applying an Agricultural Approach to Silvicultural Research

The process by which the discipline of silviculture developed and adapted new practices and techniques has been very influential in how the discipline operates and how it views forested ecosystems. During the early development of silviculture, the refinement of individual silvicultural practices was based on long-term observation and local trials. The emergence of distinct silvicultural systems was not the result of a grand research effort to determine practices that could be implemented widely. Rather, silvicultural decisions, and therefore also silvicultural systems, were developed by refining local practices and experiences. Early local adaptation was not part of formal scientific experiments but rather an inherent part of application. This history is reflected in the intricate naming protocols employed by German foresters to describe site-specific modifications to even- and uneven-aged silvicultural systems (see chap. 1).

Contemporary silviculture is described as the *art* and *science* of managing forests (e.g., Smith et al. 1997). The art can be thought of as application of knowledge that is based on careful observation and long-term practice. Knowledge was gained from experience, which provided silviculturists the ability to match or modify existing successful practices to new management conditions. The art of silviculture become so ingrained in early practice that the word *Götterblick* (literally "God's insights"; often translated as "forester's belief") was used in the German language to describe when forest management decisions were based on experience, rather than on formal empirical relationships (Abetz and Klädtke 2000; Freise 2007). The strongest present-day example of the art of silviculture can be seen in the close-to-nature movement centered in Europe (Jakobsen 2001). Lacking a strong scientific database, this movement relies heavily on experience and a deep understanding of local conditions (Thomasius 1999; Jakobsen 2001).

The dependence on insight and experience for practice development resulted in a mind-set among silviculturists that relied heavily on tradition. For silviculturists to gain and utilize long-term experiences requires continuous employment in the same position or at least in the same region. In central Europe, during the nineteenth and twentieth centuries, it was quite common for silviculturists to manage the same forest throughout their career, in many cases for multiple decades. Furthermore, it was not uncommon for positions to be handed down within a family from one generation to the next. While careful observations and long job tenure ensured continuity of practices, it also resulted in silviculture becoming steeped in tradition.

Although this structure of the profession fostered long-term application of locally adapted practices, it did not encourage critical and innovative thinking (Brang 2007). Nor did the onset of formal education for silviculturists necessarily encourage innovative ideas and approaches. Instead, formal education led to greater regional (and later global) standardization of selected silvicultural practices. The emphasis on longstanding traditions is likely one reason why silviculture does not easily adjust to rapidly changing societal values. On the other hand, many silviculturists, correctly, still see these traditions as one of the strong assets of their profession. There are clearly trade-offs between using tried-and-true practices compared to switching to more short-term, flavor-of-the-day approaches.

Starting in the early part of the twentieth century, forest research stations were established and a scientific research approach began to be applied to silvicultural topics. The onset of formal scientific inquiries in forestry was closely linked to the development of experimental and statistical methods in agriculture, as "silviculture is to forestry as agronomy is to agriculture" (Smith et al. 1997, 3; see also Cotta 1816). In that context, silvicultural research borrowed heavily from agricultural research techniques, which were developed and employed to improve agronomic methods with the main purpose of maximizing farm crop yields.

Silvicultural research and associated educational efforts were strongly influenced by experimental and statistical advances. Most notably, contemporary statistical procedures for agronomy were developed and refined by the statistician Sir R. A. Fisher (1890–1962) at the Rothamsted Agricultural Experimental Station, England. Between 1919 and 1935, Fisher pioneered the design of experiments and analysis of variance (ANOVA). Silvicultural researchers were trained to use the classical agricultural experimental designs, including completely randomized, randomized block, Latin square, factorials, or variations such as split-plot designs (e.g., Petersen 1985). Silvicultural research today remains very much dominated by these statistical approaches and the use of designed experiments with all their strengths and limitations. Designed agricultural experiments and the associated analytical methods were originally developed to find techniques for increasing annual crop yield within agricultural fields. These experiments are therefore most appropriate when silviculturists are mainly interested in higher timber yields.

Agricultural experiments are designed to find a new practice, or best treatment, that optimizes a desired outcome, usually increased yield. An example of the application of agricultural experiments in a forestry setting is a study to determine whether exotic tree species will yield more than native tree species. Researchers would set up an experiment using one of the experimental designs developed by Fisher and test whether there is a statistically significant difference in stand yield between selected exotic species and the favored native species. The experiment is actually testing whether the null hypothesis (no difference exists in average yield calculated across all replications) among the tree species can be rejected. Null hypothesis testing to identify a "best treatment" is a cornerstone of the designed experiments used in agricultural and silvicultural science. If the null hypothesis is rejected, the new best species is expected to outperform others in operational plantations. Silviculturists who utilize this new information will plant the new best species, until yet another best species can be found through experimentation.

Null Hypothesis: Results of silvicultural experiments that rely on ANOVA are either a rejection of the null hypothesis or a failure to reject it. The researcher desires to prove that one of the new treatments will be superior (i.e., the null hypothesis will be rejected) and be suitable for broad application. Such experiments are not designed to assess the relative strength of observational support for alternate hypotheses. Despite considerable criticism of null hypothesis testing (Hilborn and Mangel 1997; Burnham and Anderson 2002; Johnson and Omland 2004; Stephens et al. 2005; Canham and Uriarte 2006), it remains the dominant statistical approach used in silviculture.

Designed agricultural experiments that do not reject the null hypothesis are often considered a failure. First, they don't show progress—after all, the study did not lead to an improvement in management practices. Second, questions arise about whether limited sample size, high variability in study conditions, or other experimental constraints are responsible for the results. Third, studies that don't reject the null hypothesis are harder to publish (Csada et al. 1996). Researchers using null hypothesis testing are under pressure to find statistically significant results.

The use of designed experiments and null hypothesis testing by silvicultural researchers has strongly influenced the way field silviculturists view and implement silvicultural prescriptions. To fully appreciate the impacts of the agricultural research model on silvicultural practices, it is important to understand the suite of factors implicit in such designed experiments. These factors include null hypothesis testing, a defined suite of treatment factors, a limited set of treatment levels, the need for homogeneous treatment plots, the control of stochastic factors, and inference scope. We now discuss each of these in turn.

Thinning Studies: Probably one of the oldest types of silvicultural experiments. The recent controversy about thinning responses, initiated by Zeide (2001a) and followed up by letters and discussions in numerous settings, highlights limitations of agricultural research approaches. The discussion pointed out that the regression approach is not intrinsically different from ANOVA with all its assumptions and limitations. Zeide (2001b) suggests that after "centuries of research" we still do not understand the basic patterns of tree and stand responses to thinnings. He points out the "little utility" of empirical regression equations because they are "tied too closely to specific species, age, site, and other circumstances to be of general interest" and while being a "useful, heuristic tool . . . regressions are of little value to our knowledge." He proposes "conceptual generalizations based on the understanding of the involved processes" to avoid "going in circles."

In order to efficiently search for a new best treatment via null hypothesis testing, researchers can usually examine only a few treatment factors and/or treatment levels. The selection of the treatment factors and levels from an unlimited set of possible options can greatly influence the study conclusion. For example, a density study that compares stands with 100, 300, and 600 trees per hectare is more likely to find statistically significant differences than the same study setup with 200, 300, and 500 trees per hectare, and thus may come to different conclusions about impacts of density management. This shortcoming of null hypothesis testing becomes more limiting when issues are addressed that may entail interacting components, such as what factor, agent, or process is responsible for thinning responses or growth or mortality patterns. Furthermore, null hypothesis testing provides silviculturists with an implicit message that "scientific management" could simply imply picking the treatment from a limited set of possible options that performed best in experiments.

Types of Silvicultural Experiments: Most silvicultural studies fall into one of three broad groupings. First, and by far the most common, traditional agricultural experiments searching for a best treatment; for example, which thinning regime maximizes merchantable yield? Second, studies aimed at finding the best condition for a desired result; for example, seedbed requirements for good germination and early survival. Third, studies conducted across some type of gradient of conditions; for example, growth rates of juvenile trees under varying light levels or under different overstory canopy tree densities. It is only recently that gradient studies have become more common.

The assumptions of experiments using traditional agricultural experimental designs include high within-treatment unit homogeneity and provide a strong incentive for researchers to establish their studies on uniform or very comparable sites. Experiments with highly homogeneous conditions are statistically more powerful in finding significant treatment effects. Any review of the literature in silviculture in academic journals such as the *Canadian Journal of Forest Research*, *Forest Science*, or *Forest Ecology and Management* will show that silvicultural researchers aim to select sample plots that are as uniform as possible with respect to their soils, slope, aspect, and disturbance history for testing experimental treatments (e.g., q-factor, planting stock types, vegetation control levels, thinning densities). In our experience, finding uniform areas to test new silvicultural practices is often the most difficult task when implementing experiments, especially when working in unmanaged forests. For example, the optimal experimental setup to examine influences of stand density on tree growth would have perfectly uniform site conditions across all sample plots combined with minimal genetic variation among study trees. In practical terms this results in thinning studies being limited to the interior portions of single-species stands. Multispecies stands, stand edges, gaps, disturbed areas, or unique areas such as wetlands and riparian zones are carefully avoided to decrease variability within the study, even though they may be a vital part of the landscape.

Just as within-treatment variability in site condition and study objects is undesirable in experiments, the statistical approach also requires researchers to rigorously control any external factors that might influence experimental treatments. For example, in a long-term spacing trial designed to determine optimum planting densities to maximize merchantable volume, researchers might build a fence to protect seedlings from browsing damage. Similarly, any trees affected by insects or disease would be excluded from the analysis. Studies in which variation due to other exogenous (nontreatment) factors is very large are considered problematic because they interfere with the ability to accept or reject the null hypothesis. Frequentist statistics thus encourage researchers to minimize the variation of all factors with the exception of the experimental treatment.

The characteristics of agricultural experiments discussed above further encourage homogeneity in management as they promote studies with a limited inference scope. Information about the range of conditions (e.g., site type, aspect, elevation, species) to which study results apply is the scope of inference of an experiment. If the inference scope is narrow, results should be applicable only to those narrow conditions. Designed agricultural experiments have to consider the balance between statistical power to find difference and wider applicability of study results (Ganio and Puettmann 2008). Typically, researchers first decide on their inference scope and then lay out an experiment to ensure that treatment conditions across replications reflect the inference scope. The frequentist statistical approach is more likely to find treatment differences when the variation in external factors and the resulting experimental error are small. This will be the case when replicates are more similar; that is, the inference scope is small. For example, vegetation control studies are more likely to find significant impacts of competing vegetation when the study sites all have the same moisture and nutrient conditions.

Intensive highly controlled silvicultural studies can likely cover only a small portion of sites and will not necessarily reflect all the variability in conditions found in natural forests or even most managed stands. Natural forests and plantations are almost always much more heterogeneous than the experimental conditions where a particular treatment is tested. Most silvicultural publications do not provide specific descriptions of the inference scope (but see Cissel et al. 2006). Instead, information about the inference scope must be gleaned from study site descriptions. It is typically left up to readers of scientific reports to decide whether the study conditions are similar enough to their area of interest to make the study results applicable. Consequently, practicing silviculturists had to become comfortable with applying best treatments based on information from a limited number of experimental studies, often with very small inference scopes.

The use of traditional agricultural experimental designs and the search for best treatments has had a profound but largely unrecognized influence on how forests are managed throughout the world. Probably the greatest influence of the agricultural research model on silvicultural thinking was the implicit message that an identifiable best treatment or suite of practices exists for a particular management situation. When silviculturists attempt to reproduce results achieved in experimental studies on larger scales, such as landscapes, the agricultural research model encourages them to apply the best treatments consistently to all stands, rather than to embrace or adopt a variety of different silvicultural approaches. The adoption and dominance of the agricultural research model has not led to a culture of trial, innovation, or examination of trade-offs among practicing silviculturists, but has supported a conservative culture of implementing standardized prescriptions.

The history of implementation of silvicultural systems around the world provides an appreciation of the influence of the agricultural research model on contemporary silviculture. First, many aspects underlying the agricultural research model were already well-established in forestry long before the development of scientific silvicultural research. For example, silvicultural systems were descriptive management systems that included the harvesting, regeneration, and tending methods needed to create specific types of even- or uneven-aged stands. They already had many characteristics that later became indicative of the agricultural research model, including a limited set of treatments, a bias toward uniformity, and a focus on mean responses.

An important distinction needs to be highlighted. In Europe, where the individual silvicultural systems evolved well before the development of the agricultural research model, application procedures did not focus on widespread applications of a single best treatment (with notable exceptions, see chap. 1). European silviculturists are still more apt to incorporate small-scale variability into individual systems based on long-term observations, local experience, and new ecological knowledge (e.g., Pommerening and Murphy 2004). In contrast, application of silvicultural systems outside Europe, for example in Canada or the United States, began mainly after the agricultural research model had become solidly entrenched in silvicultural thinking. Individual silvicultural systems were thought of in terms of a prescribed program of fixed treatments and, in general, local modifications and adjustments were not encouraged. Furthermore, throughout the twentieth century, educational material relied on scientific studies that determined best treatments for particular species or regions. For example, the series of U.S. Forest Service manager's handbooks in north-central states (e.g., Benzie 1977; Perala 1977; Sander 1977) provided silviculturists with fixed sets of possible treatments for the major commercial tree species. These guides and other subsequent guides were powerful teaching tools and provided students and practicing silviculturists with a quick way to become familiar with local silvicultural constraints and opportunities without necessarily having to visit the woods. On the other hand, such guides further ingrain the belief in a best treatment; they emphasize knowledge over thinking, and are not designed to encourage innovation or local adaptation as an inherent part of practice.

In many parts of the world, the widespread application of uniform silvicultural systems combined with the use of designed experiments to identify best treatments for individual practices or suites of practices has resulted in fairly homogeneous conditions in terms of tree species and stand structures within and among managed stands. This is especially the case for plantation management, for example large-scale industrial forestry operations in North and South America, where the same species is planted at the same density on tens to hundreds of thousands of hectares. But, it also applies to other even-aged systems and uneven-aged forest management systems where variability is purposefully reduced and controlled through management. Even the *Dauerwald* movement (see chap. 1) or its derivations, close-to-nature forestry, minimizes variation within and among stands by emphasizing a limited set of possible stand structures for all stands and conditions.

The Scale-Independent View of Forestry Practices

The assumption of scalability is implicit in agricultural experimental designs and has also influenced how silviculture relates to homogeneity. Much of the silvicultural science and management has been within the disciplinary structure of universities and government forest agencies responsible for forest management. Within this disciplinary structure, there are established, though constantly evolving, norms for good science and management. As previously discussed, silvicultural science has been heavily influenced by the agricultural research model resulting in the strong belief that information describing structures, relationships, or processes in forest ecosystems can be derived from small experimental plots and then be easily scaled up to stand or landscape levels.

Researchers working in small and very homogeneous plots are not concerned about scaling up when experimental conditions are closely reflecting situations where the results will be applied. In these instances, calculating the average response on small plots likely provides information applicable to similar but much larger units, for example, agricultural fields. As silvicultural researchers adopted this research model, they implicitly accepted that the study of practices in small plots provides reliable information to guide management at much larger scales. This assumption of linear scaling further influences how silviculturists viewed homogeneity in forest ecosystems. If the assumption of uniformity across scales is met, results from small research plots can be scaled up and operational practice would be expected to yield the same results as the designed experiment. Being able to use scientific findings only by scaling up sends the message that study conditions (i.e., uniform stands) are the norm and an inherent requirement of good "scientific" forest management.

With very few and mostly recent exceptions (e.g., see listing of large-scale experiments in chap. 4), silvicultural research plots were much smaller and more uniform than the stands to which the results were expected to be applied. Most silvicultural studies during the 1960s to 1980s utilized small plots (e.g., 0.1-hectare plots for the Level of Growing Stock Study, Marshall and Curtis 2002). From an experimental viewpoint, the use of small plot sizes had several advantages. It made it easier to locate homogenous areas and to increase the number of replicates. It allowed more efficient use of land, labor, and other resources needed for research. Scalability from research plots to managed stands was further enhanced by use of scale-independent measurement units (e.g., trees per hectare) that could be directly translated into stand-scale activities (see earlier discussion on stand management and stand descriptors).

Discrepancies between results of applications in small, highly controlled growth and yield research plots versus stand-scale applications have been known for a long time. For example, Bruce (1977) suggested that a solution to the problem is to make managed stands more uniform and thus more similar to the research plots. In effect, the problem of scaling up encouraged and promoted the management of homogeneous stand conditions.

Large-scale operational application of new silvicultural treatments that proved superior under limited study conditions can also produce different results than predicted. For example, the yield that can be expected from managing the sugar maple (*Acer saccharinum*) forests of Québec by the single-tree selection system (*coupes de jardinage*) has been carefully studied using replicated experiments (Bédard and Brassard 2002). Operational implementation of the treatment that proved best in the experiment did not produce the predicted results when applied widely by forest companies. Physical damage during logging, thinning shock, and individual stem mortality due to windthrow were found to be, on average, much higher in operational areas than in the experimental setting. Some operational stands produced similar results to those found experimentally, but overall there was considerably more variability in the operational logging, resulting in greater variability in yield. Scaling average responses from small experimental plots can be inadequate to characterize and understand important processes that control growth responses in naturally diverse forests. A general analysis of scaling-up issues continues to receive little attention in silviculture research.

An alternative approach to research that averages variability and focuses on uniform application at the stand scale is to tailor research and prediction to the spatial scale of interest. For example, one of the most important events silviculturists must understand and predict is the recruitment of new tree seedlings, which likely needs to be studied at multiple spatial scales that are not necessarily related (Houle 1998). Seed availability is largely influenced by the nearby abundance of parent trees acting on spatial scales ranging from a few meters for heavy-seeded species (e.g., oaks, chestnuts) to a few hundred meters for the vast majority of species with lighter, wind-distributed seeds (Greene et al. 2004). Seed dispersal distances, and therefore the appropriate scale of study, can be further influenced by stand structure (Clark et al. 1998; LePage et al. 2000). Alternatively, seedbed substrate varies at the microsite scale, but substrate favorability can also be strongly influenced by local canopy structure (Cornett et al. 1998; LePage et al. 2000).

The study of tree growth in small uniform plots can lead to the conclusion that competitive forces are applied equally throughout the stand, which encourages the viewpoint that spatial variability at scales smaller than stand-level is not important. For example, growth and yield researchers have repeatedly tested whether integrating small-scale spatial variability in growth models improves model predictions. In comparative studies of distance-independent and distance-dependent competition indices, they generally concluded that spatially explicit, distance-dependent competition indexes provide no worthwhile improvement over spatially independent models (Daniels 1976; Alemdag 1978; Lorimer 1983; Martin and Ek 1984; Daniels et al. 1986; Corona and Ferrara 1989; Holmes and Reed 1991; Wimberly and Bare 1996). Results of comparative studies suggest that the spatial configuration of trees within a stand is not important for predicting individual tree and stand-level growth. Among other possibilities, this conclusion likely highlights the limited spatial and size variability found in plots utilized in these comparative growth studies. As discussed earlier, when studies use the agricultural model to investigate impacts of stand density on growth and yield, it is desirable to keep other factors, such as spatial arrangement, as homogeneous as possible. Thus, unless specifically designed to investigate spatial arrangement, the research approach is biased against accounting for the effects of within-stand spatial variability. The generally accepted validity of many growth models that assume de facto regular spacing leads to the impression that small-scale spatial variability is not important in influencing stand development and has resulted in the belief that fine-scale spatial variability can be ignored when managing forest stands.

Competition Indexes: Most growth models do not explicitly account for the presence of spatial structure in tree data, but rather use competition indexes to incorporate information about a subject tree and its neighbors. Distance-independent indexes are simply functions of stand-level variables or dimensions of the subject tree. Distance-dependent indexes use neighborhood-scale information in an attempt to capture fine-scale changes in competition due to the distance between the neighbors and the subject tree and their relative or absolute dimensions. See Moeur 1993; Shi and Zhang 2003; Stadt et al. 2007.

Focus on Predictability

In general, over the last two centuries silviculturists have successfully provided a steady and predictable flow of timber and wealth. To accomplish this, silviculturists had to limit the influence of stochastic disturbances, refine regeneration and stand tending practices, and emphasize homogeneous stand conditions. These practices also reduced the variation in stand-level responses. One key reason for homogenizing the temporal, spatial, and structural components typically found in natural forests was the need for increased predictability of stand development and therefore of yield.

Efforts to predict yield have always been crucial for assessment of silvicultural practices. Since its very beginnings, the historical development of silviculture has been closely linked with concerns to ensure sustainability of wood supply (von Carlowitz 1713) and these needs led to the development of the normal forest concept (see earlier discussion and chap. 1) and other tools for forest planning. For example, in the early twentieth century in parts of North America, "Hanzlik's formula" was applied to ensure that ongoing harvest rates resulted in the conversion of forest estates to a normal forest and that equal annual volumes of timber were available in perpetuity (Hanzlik 1922). By now, most regions have moved beyond Hanzlik's formula to include social, economic, and environmental considerations in their calculation of wood supply.

The calculation of a sustainable harvest rate requires reliable information about tree and stand growth through repeated inventories, growth and yield models, or some combination of the two. It also requires silvicultural practices that ensure reliability and consistency of regeneration and tree and stand growth patterns. To ensure timely natural regeneration, early silviculturists developed reproduction methods to promote and enhance a reliable seed supply and to provide optimal conditions for the natural establishment of preferred tree species (e.g., seedtree or shelterwood; Matthews 1989; chap. 1).

Developments in the United States and Canada during the late twentieth century provide good examples of how large-scale industrial logging activities impacted the reliability of natural regeneration and how, in turn, these concerns were addressed by silviculturists to ensure predictable regeneration (see Cleary et al. 1978; Lavender et al. 1990; Wagner and Colombo 2001). In many parts of North America, natural regeneration was considered not consistent enough. To improve reliability and predictability of regeneration in regions where clearcutting large areas became a widespread practice (e.g., Weetman and Vyse 1990), silviculturists developed tree nurseries and planting programs for selected tree species and increased research efforts to ensure more consistent reforestation than naturally occurs after harvesting (Thompson and Pitt 2003).

As part of these efforts, the regeneration phase, from seed storage to germination and early seedling growth, was moved into tree nurseries or greenhouses. Rather than allowing for stochastic elements such as predation or weather to influence early seedling establishment, these factors were controlled. Greenhouses provided a perfect, climate-controlled setting where light, nutrient, and water levels could be managed. With proper seed collection and storage, germination conditions, and protection from insects, diseases, and weeds, nurseries became efficient at producing reliable and homogenous planting stock. Planting tools, site preparation techniques, and vegetation control practices were refined to ensure a high survival rate of planted seedlings. In regions with intensive forest management, the combination of vigorous planting stock, site preparation, and vegetation control regularly results in higher than 90 percent survival of planted seedlings.

Efforts to improve predictability also focused strongly on aspects of tree and stand growth (Rudolf 1985; Curtis et al. 2007). Inventory plots and growth and yield experiments were installed in response to the need for long-term predictability of tree and stand growth. The development of growth models followed in some regions. To promote predictability and reflect "ideal" management scenarios, growth models were mostly based on data from small, uniformly structured research and inventory plots (see also scale discussion earlier). Furthermore, when data were used in the analysis of studies or pooled from various studies to develop a regional growth model, only those sample plots that had maintained their integrity (had experienced no or limited disturbances) were used in the analysis (e.g., Buckman 1962; Pretzsch 2005). It was not uncommon for individual trees, plots, or entire replicate units to be dropped from growth and yield experiments if outside factors such as herbivory, disease, or windstorms increased variation, thus reinforcing the notion that managed forests should be free of unplanned disturbances. In reality, it may be rare for any stand, managed or unmanaged, to remain totally free of insects, disease, or storm damage for extended periods of time.

Most early yield tables and growth models were capable of making predictions only for single-species even-aged stands due to a combination of the use of agronomic study methods and limited computer power. Many models used today to predict growth rates still have that limitation, which creates an interesting dilemma. If determining sustainable harvest levels is deemed important, and reliable growth predictions are available only for single-species simple structured stands, then simple structured stands are favored by silviculturists. This dilemma can be avoided by investment in a sophisticated permanent inventory of a wider range of stand types (e.g., continuous cover forestry) or development of more complex growth models. In general, the restriction of growth models to predicting yield under only uniform conditions has encouraged the simplification of practices and homogenizing of structures in managed stands. The measurement of growth in permanent inventory plots may not have the same limitations as single-species growth models in terms of dealing with mixed-species stands. However, as long as inventory plots aim to determine maximum sustainable yield levels, the underlying premise still reflects silvicultural thinking that fully stocked, evenly spaced stands are the norm or reference condition and deviation from this norm is then considered bad forestry.

This norm or reference condition on which yields are projected may be an artificial or idealized condition that doesn't actually exist. For example, almost half (45 percent) of wood harvested in 2004 on intensively managed state land in Baden-Württemberg, Germany, was unplanned and in response to disturbances (Anonymous 2005). Indirect effects of climate change, such as when responses of one species to a climate trend in turn affect different species, provide another example. Woods et al. (2005) describe strong evidence that the fungus *Dothistroma septosporum*, in response to a directional increase in summer precipitation, is negatively impacting lodgepole pine plantations in a completely unexpected way. Yield projections need to be reassessed for extensive well-stocked pine plantations, now defoliated or dying because of the fungus after an increase in summer precipitation, which would be expected to favor tree growth.

Small- and larger-scale disturbances are an integral part of a landscape, and their effects on stand development cannot be predicted from growth models that assume fully stocked, regular stands. Most forests exhibit a pattern of disturbance-induced change that spans virtually all scales of space and time (Frelich 2002; Kimmins 2004; Johnson and Miyanishi 2007). If the norm is a fully stocked, homogeneous stand, disturbances are necessarily viewed as an external factor that negatively influences stand development, rather than as an integral part of stand and landscape development. This also creates an interesting discrepancy between the effort put into producing growth models with high accuracy and the rough corrections that are often used to account for the impact of stochastic elements.

The emphasis on predictability could be addressed by silviculturists only through control and homogenization of forest structures, and this focus has infiltrated all aspects of silviculture. The resulting top-down, command-and-control approach to silviculture is still deep-rooted in the discipline and difficult to overcome. The focus on predictability is not unique to silviculture and forestry. It is observed in most, if not all, renewable resource management disciplines that involve a harvest of a surplus (e.g., yearly harvest levels for wildlife and fisheries management).

The histories of forestry, fisheries, and wildlife management share similar patterns in this regard (Ludwig et al. 1993; Hilborn et al. 1995; Bottom et al. 1996; Struhsaker 1998). However, the link between predictability and a top-down, command-and-control approach weakens as increasing computer power, computational skills, and new technologies allow development of more sophisticated growth models and inventories that do not rely on homogeneous stands or the normal forest concept.

Command and Control: The tendency to apply increasing levels of top-down management to natural resources. It manifests itself in attempts to control ecosystems; and when ecosystems act in ways that are considered erratic, even more control is applied. Command and control often, however, results eventually in unforeseen consequences for ecosystems. The pathology of natural resource management is the loss of ecosystem resilience when the range of natural variation in the system is reduced. If natural levels of variation in system behavior are reduced through command and control, the system becomes less resilient to external perturbations, resulting in crises and surprises (Holling and Meffe 1996; Folke et al. 2004; Drever et al. 2006).

Conclusion

Silvicultural practices over the past few centuries have been adapted to a wide variety of objectives and conditions, but throughout its development silviculture has relied on several core principles. First, it has been predominantly tree-focused in application and assessment of practices. Second, it treated stands as homogeneous entities. Third, it utilized the agricultural research model in evaluating old and new practices. Fourth, it assumed that spatial scales are unimportant and that stand-level assessment and management were appropriate for all situations. Finally, it focused on achieving orderly and predictable forest development. These principles cannot be viewed in isolation from each other and from the influence of long traditions in silviculture. In conjunction, they have directly and indirectly affected how research is undertaken and have profoundly influenced how silviculture is taught to students and how practicing professionals think and act.

The shortcomings of the reliance on the above-described principles have become apparent with increased interest in a wider variety of ecosystem values, processes, and functions and a better understanding of forest ecosystems, especially of ecosystem health, productivity, and resilience. The current approach to silviculture research and management as described in the five principles has inherent characteristics that promote uniformity and discourage variability. This, in turn, has resulted in many managed forests having uniform or narrow ranges of tree species composition and stand structures. Thus silviculture, with its desire to control nature and ensure predictability, is an example of a discipline that has slipped into what Holling and Meffe (1996) termed the "pathology of command-and-control management in the natural resources." Furthermore, the reliance on long traditions and the associated conservative culture of silviculture has made it especially hard for silviculturists to respond to rapidly changing ecological knowledge, management objectives, or social views of forests.