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THE SCIENTIFIC BASIS OF FORESTRY

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> A sufficiently wise and flexible silvicultural art can be developed on the ground only by practitioners who understand the forest as a biological entity.
>
> F. S. Baker (10)

> ...the existing level of knowledge about forests is inadequate to develop sound forest management policies.
>
> National Research Council (114)

ABSTRACT

Over the past two decades forestry in the United States has diverged into two approaches with quite different objectives and scientific priorities. The management focus of most industrial lands is on increasing productivity of wood fiber via plantations and various cultural tools, especially genetic selection, fertilization, and control of noncrop vegetation. Federal forest management has shifted from a similar focus to greater emphasis on protecting diversity and water. Issues of long-term sustainability are important regardless of ownership. Science has played and continues to play a fundamental role in all aspects. Selection for fast-growing genotypes has increased yields on the order of 10% to 20% depending on species. Fertilization often increases growth significantly but responses are variable and difficult to predict. Significant questions remain concerning the sustainability of intensive forestry, particularly when practiced over wide areas. Soils are heavily impacted by some harvesting practices, and the degree to which damage can be repaired by fertilizers is an important scientific issue. Intensive forestry often results in increased pest problems. In at least one case (fusiform rust in southern pines), a pest has been contained by selecting resistant cultivars, a situation that may or may not be evolutionarily stable. Species diversity is clearly reduced under

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intensive management, raising questions about the functional role of species with no commercial value. Many of the questions facing forestry science—particularly those dealing with the relation between complexity and function—are precisely the ones confronting basic ecology. Over the past decade scientists have labored to develop ecosystem-based management approaches that maintain system complexity and function, and scientists have increasingly played nontraditional roles at the interface between biology, sociology, and policy.

INTRODUCTION

Forestry has been defined as "the scientific management of forests for the continuous production of goods and services" (10), though, as with agriculture, forestry that reflects the specifics of place as well as the generalities of science necessarily involves art. Biologic, physical, social, management, and engineering sciences all play an important role in forestry. Over the past 20 years the scope of biologic and environmental sciences contributing to forest management has expanded beyond ecophysiology, genetics, and vegetation management to encompass soil processes, ecosystem structure and dynamics, hydrology, wildlife biology, fisheries, restoration ecology, conservation biology, and landscape ecology. The social sciences, once relegated to a backseat (except for economics), are now seen as critically important, at least on public lands in the United States. Research into innovative engineering techniques and the development of a broad array of forest products are essential parts of the contemporary package, and management science is playing an increasingly important role in helping to integrate science, economics, and politics. A new dialogue among science, philosophy, and religion is exploring the esthetic/spiritual dimensions of forests—and nature as a whole—that have been common to humans for millenia.

In this paper I deal mostly with biology, soils, and hydrology, but with the understanding that sociology, esthetics, ethics, spirituality, economics, and history intertwine with virtually all aspects of the biologic and physical sciences to produce the complex systems that foresters work with and within. Ignoring that basic truth during much of the twentieth century has resulted in social and political turmoil throughout the world over the way forests are managed—eventually triggering a fundamental reevaluation on the part of foresters and forest scientists of what forestry is all about (88). The need for integrating a broad array of scientific disciplines to guide forestry, indeed all natural resource management, has never been more acute.

This paper is basically a story of the changing role of science in forestry and an assessment of the current state of knowledge and priority needs. I discuss what I believe to be the most important challenges facing forestry science; however, the breadth of the topic does not allow all aspects to be given their rightful due. My choice of emphases reflects my own experience and biases; someone else may have made different choices. I focus mostly on North America—though both the practice and science of forestry are largely global affairs—because, until recently, the basis strategy of forestry has largely been the same everywhere during the latter half of the twentieth century.

A SHORT HISTORY

Forestry as a science originated in Europe during the latter eighteenth and early nineteenth centuries, largely in response to the poor condition of Europe's remaining forests and an impending wood famine (126). From early on there were competing philosophies about the proper approach. Aldo Leopold, who once supervised a US National Forest, described two types of forestry: Type A sees "... land as a commodity and trees as cellulose to be grown much like cabbages"; Type B "... treats land as a community of interacting and interdependent parts, all of which must be cared for" (quoted in 12). Type B, which I refer to as ecosystem-based forestry, has always had a strong philosophical representation within the forestry profession; however, Type A has predominated throughout the world during the twentieth century. Like modern agriculture, its focus has been on the properties of individual ideotypes rather than communities and ecosystems (119). Type A is commonly referred to as intensive forestry (where "intensive" refers to cultural inputs).

Intensive forestry had its beginnings in Germany during the mid-1800s. German forest scientists, motivated by the ideas of the English economist, Adam Smith, formulated an economic approach called soil rent theory, which held that interest should be earned on land, timber capital, and silvicultural expenses (in opposition, "forest rent" theory held that interest charges against these assets were inappropriate). Plochmann (126) describes the result. "The soil rent method furnished foresters with an ideal planning tool for calculating the species with the highest monetary return and the financial rotation with the highest internal rate of interest on a given site. It fit perfectly with classical liberal economic theory, which set the maximization of profit as the general objective of economic activities and therefore the general objective for forestry as well." In central Europe, native hardwood and mixed hardwood/conifer forests were cleared and planted to monocultures that grew fast and produced high value—mostly Norway spruce. Because interest was charged on land and other capital assets, the rotation length (time period between regeneration of a stand and final harvest) yielding the highest rate of return was much shorter than the normal life span of forests.

Despite some misgivings on the part of both foresters and the public (12), intensive forestry took root in North America following World War II, and by the 1950s was firmly established on both industrial and public lands. Over time it became the dominant theme in most or all of the nation's forestry schools. The reasons behind the ascendancy of intensive forestry were clear. A primary responsibility of foresters was to supply the fiber needs of a rapidly expanding economy, and this would best be done through plantation monocultures of fast-growing tree species. The full growth potential of land could be ultimately achieved by planting healthy, genetically superior seedlings, controlling non-crop vegetation, enhancing site quality through fertilization (and other techniques where necessary and affordable), and clear-cutting when either rate of tree growth or economic returns calculated for a series of rotations were maximized (e.g. 40). The responsibility for meeting the demands of a rapidly growing market without overharvesting or otherwise degrading future productive capacity fell to scientists, and intensive forestry came to be described by many of its proponents, and more recently some critics, as scientific forestry. In a narrow sense that characterization is accurate, as the tools of science are used, albeit in the service of a particular economic model. However, like crop-centered agriculture, intensive forestry was not derived in the context of testable hypotheses about alternative approaches, nor was there much open debate about alternatives (until lately); thus in a more fundamental sense it is not scientific. Not surprisingly, forestry shared one of the central distinguishing features of industrialism: uncritical acceptance of the untested hypothesis that maximizing economic efficiency in the short term was the path to maximizing social and economic benefits into the future.

The last 35 years have seen much change in forestry and a significant divergence in approaches. During the 1960s, Germany, for social, environmental, and economic reasons, began converting state lands back to the native hardwood/conifer mixed forests and growing high-value trees on long rotations (126). In the United States, beginning in the late 1960s and continuing to the present, public opposition to clear-cutting and herbicides joined mounting scientific evidence that, in contradiction to federal laws, native diversity was not being maintained on federal lands; together these led the US Forest Service (USFS) and the Bureau of Land Management (BLM), after significant prodding by the courts to adopt ecosystem management as official policy. Although some companies have adopted aspects of ecosystem management, intensive forestry remains by far the most commonly used approach on industrial lands. (They do not necessarily incorporate all aspects; fertilization and herbicides in particular may or may not be used, depending on perceived economic benefits.) Thus, over the last decade in the United States what was once a single approach has diverged into two paths that, while still sharing some aspects, differ significantly in objectives, approach, and scientific priorities.

STATE OF KNOWLEDGE

The biological sciences have played three distinct roles in forestry: improving growth through intensive cultural practices; researching the environmental impacts and sustainability of intensive forestry; and, most recently, developing a science of ecosystem-based management, which includes a broad array of basic and applied research dealing either directly or indirectly with alternative management approaches. Each of these will continue to be important in forestry, though their relative importance is shifting from crop-centeredness to a greater balance between traditional forestry research and the science of ecosystem-based management. Questions of sustainability remain of central importance regardless of management approach.

Improving Growth

The basic approaches to increasing stand growth are (*a*) rapid establishment of a new stand following harvest (nursery and planting practices); (*b*) maximizing the flow of site resources to the crop (controlling competing vegetation); (*c*) improving soil resources (fertilization, bedding, and drainage on some sites); (*d*) selecting and breeding fast-growing genotypes; and (*e*) minimizing losses due to insects, diseases, fire, and wind (stand protection). All approaches have been actively researched over the past 30 years, except that comparatively little research has been done on stand protection, and that almost exclusively in reaction to specific problems. The theoretical potential for productivity gains through intensive culture is significant. Farnum et al (40) calculated growth rates of unmanaged stands of Douglas-fir and loblolly pine (two of the most important commercial species in the United States) at, respectively, only 23% and 12% of what could be achieved. In this section I focus on genetics, vegetation control, and fertilization, which are the centerpieces of intensive forestry. I deal with vulnerability of managed stands to biotic and abiotic disturbances later.

GENETICS Most commercially important tree species contain large within-population genetic variation, providing a rich source for selection. For example, approximately 92% of the genetic diversity in loblolly pine, the dominant timber species in the southern United States, occurs within stands (177). A further boon to selection programs is that many individual genotypes of commercially important species have wide ecological amplitude. Loblolly pine and Douglas-fir families tend to maintain a constant ranking across a wide range of environments (101, 157); when significant GXE interactions do occur in those species it is usually due to a few families.

Much tree breeding in the United States and Canada has been through cooperatives involving industry, universities, and in some cases public agencies (e.g. 164). Although there is growing interest in cloning (155), most genetically improved conifers (by far the most important commercial species in North

America) come from seed orchards. The basic strategy is to select trees in the field with desired characteristics and propagate them in both open-pollinated production orchards and breeding orchards where select trees are interbred through controlled pollination (40). At the end of the first breeding cycle, seed from the production orchard is outplanted, while seed from the breeding orchard is used (after progeny testing) to establish second-generation production and breeding orchards, and so on. The use of elite breeding populations (progressive selection and interbreeding of the best performing genotypes), a strategy adopted from agronomic and animal programs, is increasingly common in conifer breeding (177). Various technological advances have reduced breeding cycles considerably over the past two decades—in loblolly pine from 22 years in 1974 to 7.5 years in 1994 (177). In 1992, 90% of all plantings in the southern United States, amounting to 1.5 million acres, were with genetically improved seedlings (164). The first genetically improved trees are now being harvested in the southern United States, with estimated volume gains of 12% for loblolly pine (32% in harvest value) and 18% for slash pine (73, 102). Weyerhauser Company estimates a 10% gain in juvenile height growth for select Douglas-fir in Oregon and Washington (157).

The importance of maintaining genetic diversity is much discussed among forest geneticists (e.g. 38, 102, 110, 135). Erosion of genetic diversity through random drift is an especially significant concern in forest trees, which carry high levels of lethal recessive alleles and are particularly vulnerable to inbreeding depression (93, 111). Generally one of two approaches is used to maintain diversity within breeding populations (39): the hierarchical open-ended system (HOPE) and the multiple population breeding system (MPBS). The HOPE strategy, developed originally by agronomic breeders, periodically introduces genetic material from populations early in the selection cycle to populations at later stages of selection. MPBS, developed by forest geneticists (110), sets up a number of different breeding populations and exchanges genes in controlled crosses among these—establishing what is in essence a controlled metapopulation structure. Allozyme studies in loblolly pine show that, although both strategies maintain relatively high levels of allozyme diversity within elite breeding populations, neither maintains the diversity found in natural stands (176). As would be expected, rare alleles are the most heavily impacted. Moreover, because seedlings are culled in the various steps between controlled breeding populations and the eventual planting stock, the diversity of resulting plantations will be lower yet (177). Studies of other commercial species show similar patterns: Breeding programs to date have had little or no influence on overall allozyme diversity; however, rare alleles may be sharply reduced (37, 156). Major questions remain concerning effects of selection on genetic diversity at the landscape level, or what Friedman & Foster (48) refer to as beta genetic diversity, i.e. the allozyme diversity of an elite breeding population may differ little from that of wild stands (alpha diversity), but planted over large areas the elite population could replace a fine-scale genetic mosaic, resulting in genetically simplified landscapes (48).

Any reduction of genetic diversity raises the presently unanswerable question of how much is sufficient to maintain resistance to pests and the capacity to adapt to changing environments (102, 132, 177). The adaptive value of rare alleles is unknown at present (38). Some forest geneticists argue they contribute little to overall fitness; others, however, suggest that loss of rare alleles could compromise long-term adaptive flexibility (177). Inability to relate allozyme measurements to phenotypic traits with potential adaptive value seriously limits the usefulness of allozyme measures as predictors of ecological response (135).

VEGETATION MANAGEMENT Grounded in the common view of plant community ecologists that competition is the most important interaction among plants, the focus of vegetation management in forestry has been on increasing crop yields through the use of chemicals and tillage. Considerable research (though not all) shows that controlling noncrop vegetation increases growth of crop trees during the early years of stand development, and in some cases establishing plantations can be difficult or even impossible without vegetation control (54, 171). A major thrust has been to develop competition indices relating levels of noncrop vegetation to potential growth response. However, the very short lifetime of most experiments limits the reliability of indices, which have been found to vary over time with shifting community structure (170).

The issues surrounding vegetation management are among the more complex in forestry, involving ecological effects of herbicides, long-term and indirect effects of altering community structure, and the functional roles of different plant species. As pointed out by some prominent researchers in the field, little attention has been paid to long-term and ecosystem-level effects of vegetation management (130, 170). The basic scientific issue is one of the relationship between community structure and ecosystem function, something ecologists in general are just beginning to grapple with.

In North American forestry, where conifers are the major commercial species, noncrop vegetation is virtually always broadleaved trees, forbs, shrubs, and grasses. A variety of studies have either conclusively demonstrated or strongly suggested that these plants perform numerous important ecological functions, including providing unique food (e.g. nuts, nectar), enhancing nutrient availability (9, 49), replenishing nitrogen capital through biological fixation (14, 67), stabilizing soil nutrients and biology following disturbances (5, 16), and increasing resistance of conifers to herbivorous insects, pathogens, and fire (e.g. 52, 123, 136, 146, 161, 181). The complexity of interactions among plant species is only beginning to be understood but goes far beyond simple competition. For example, it is now well established that different plant species within at least some communities—including broadleaved trees and conifers—participate in a network of shared resources mediated by mycorrhizal fungi (131, 147).

The major challenge for the science of vegetation management is to find balance between competition and other important ecological functions, and this will require a much improved understanding of interactions among plant species and between plants, animals, and microbes and how these interactions are affected by relative density, environmental factors, and time. The few studies that have manipulated relative density of crop and noncrop species show complex, shifting competitive relationships; as Shainsky & Rose (142) put it, "competition is not linear and unidirectional." Moreover, protective and stabilizing functions may come into play only during critical periods, such as during wildfire or recovery from disturbance, which means the importance of these functions could easily be missed in short-term studies (125).

Scientists working with vegetation management in forestry increasingly take an ecosystem view (the theme of the 1998 International Conference on Forest Vegetation Management is "Forest Vegetation Management and Ecosystem Sustainability"). Experiments that manipulate relative density or spatial patterns of noncrop plants or that separate shrub from herb competition are becoming more common (e.g. 103, 141). There is movement toward an "integrated vegetation management," which, like integrated pest management, seeks ways to reduce pesticide use or replace it altogether (170).

FERTILIZATION Hundreds and perhaps thousands of fertilizer trials have been installed over the past 30 years in forests of the United States and Canada; these vary widely in experimental rigor, with later installations generally better designed and more intepretable than earlier ones. A substantial number in the United States are university-industry-USFS cooperatives. Fertilization experiments are frequently coupled with other cultural treatments such as thinning and vegetation control. Most research has focused on nitrogen and, in the south, phosphorus (15), though experiments have been installed using NPK (112) and, in at least one case, slow-release multinutrient tabs (168).

N fertilization frequently produces significant, occasionally spectacular, but often highly variable growth responses. Volume gains from N average 16% to 26% in coastal Oregon, Washington, and British Columbia (104). In a regional study employing N and P in a factorial design, loblolly pine volume growth in response to N and P averaged 25% greater than controls, with NP yielding 2–3 times greater response than did the addition of N and P alone (112). A recent research trend has been to employ frequent, small additions of N, a technique shown by Swedish researchers to better mimic natural processes and produce significantly greater growth response than infrequent, large additions (80). Using that approach in a North Carolina study resulted in exceptional growth responses in young loblolly pine, doubling leaf area over a four-year period and increasing stem volume 180% compared with controls (3). Part of the growth response was due to reallocation of CHO from fine roots to above-ground tissues, a dynamic seen in other studies and probably quite general. Despite a droughty site, irrigation had a relatively small effect in the North Carolina study, suggesting that other cases in which water is thought to be limiting may actually be N limited.

Predicting fertilizer response has been a problem area and the subject of considerable research. Although N has enhanced tree growth in 70% of trials in Oregon, Washington, and British Columbia, the magnitude of response varies widely (104). Similarly, researchers have had limited success in predicting growth response to N and P in the southeastern coastal plain (66). Standard measures of soil nutrient availability are seldom useful (66, 144), while foliar levels may or may not be. Evidence from both the south and the west indicates that limited response to N and P is often due to deficiencies of other nutrients, with potassium, sulfur, boron, magnesium, and iron identified in one or more studies (e.g. 112, 144, 168). Recently, DRIS norms have been employed with some success to classify the Douglas-fir stands with regard to their response to N fertilization (144). DRISS, originally developed by agronomists, uses nutrient ratios in foliage or soil to predict fertilizer response.

TREATMENT COMBINATIONS Cultural practices are usually applied as sets, i.e. a single site may be drained, fertilized, herbicided, and planted with genetically improved trees. Some research has shown non-additive responses to treatment combinations. For example, trees may not respond to fertilization unless stands are thinned or competing vegetation is controlled (153). Even though GXE is minimal in loblolly pine, McKeand et al (101) argue that planting certain responsive families will significantly increase gains from cultural treatments. The degree to which intensive cultural factors interacts with ecologic factors such as long-term soil fertility and resistance to pests and pathogens is the subject of the next section.

Sustainability

Concern with sustainability in forestry dates back to the late seventeenth century; in fact, Wiersum (174) argues forestry was the first science in the western world to explicitly acknowledge the need to safeguard finite natural resources for future generations. However, achieving sustainability within an economic system that devalues the future is a particular challenge, especially for a long-term endeavor like forestry (13). Negative impacts of practices on future yields of wood can, in theory, be dealt with by incorporating them within economic calculations, though the further in the future such costs are realized the less influence they have on present net value. Impacts on nonmarketable goods (e.g. habitat, water) and risks with high uncertainty must be dealt with in other ways.

What To Sustain?

For much of the history of forestry, sustainability meant maintaining a steady supply of wood (174). In the United States considerable discussion occurred prior to and in the years following World War II about the role of forests in wildlife habitat, watershed protection, and even regional climate, but this had relatively little effect on practices (e.g. 92). The Multiple Use Sustained Yield Act of 1960 specified five things to be sustained on public lands: timber, fish and wildlife, outdoor recreation, range and fodder, and watersheds (174). More recently, sustaining biodiversity has been center stage, though that term is itself subject to various interpretations. Angermeier & Karr (9) argued that policies for achieving sustainability should focus on biological integrity, which they define as "a system's wholeness, including presence of all appropriate elements, and occurrence of all processes at appropriate rates." Franklin (44) defines sustainability as "... maintenance of the *potential* for our land and water ecosystems to produce the same quantity and quality of goods and services in perpetuity."

The following discussion focuses on four critical components of ecological sustainability: soils, water, species diversity (habitat), and resistance to disturbances (118). A fifth, evolutionary potential, was discussed in an earlier section.

Soils

German foresters knew as early as the mid-1800s that export of nutrients associated with removing forest litter reduced tree growth. Outside of Europe, however, little attention was given to the effects of forestry practices on soils and nutrient capital until the mid-1960s, when data from intensively managed *Pinus radiata* in Australia and New Zealand showed yields had declined significantly between the first and second rotations, a phenomenon eventually traced to loss of soil organic matter (SOM) and nutrients during site preparation for planting. As the same practices—hot slash burns or use of heavy equipment to push logging residues (and often topsoils) into piles—were widely used in North America, considerable research was stimulated that continues today (e.g. 11, 53, 68, 120). A group of leading forest soil scientists expressed the current view of many soil scientists and ecologists: "... intensive site preparation, increased utilization, and shortened rotations that accompany domestication carry high potential risks to the site's capability to sustain growth" (129).

Soil fertility (broadly, the capacity of soils to support plant growth) is an emergent property arising from dynamic interactions among nutrients, organic matter, soil structure (a function of both physical and biological processes), soil organisms, and plants (121). Most forestry-related research to date has focused on nutrient balances, comparing losses associated with harvest and site preparation with inputs to replace those losses. Nutrient losses associated with clear-cutting have been well documented and include three primary pathways: (*a*) direct removal in harvested biomass; (*b*) losses associated with site preparation techniques such as burning, which impacts volatile elements (especially carbon and nitrogen), or windrowing (also called raking or pile-and-burn), which displaces residual organic matter from the majority of a site onto small portions; and (*c*) export in erosion and leaching. In most cases, losses in harvested biomass and site preparation far exceed leaching and erosion (32, 97); an important exception is where early successional vegetation is prevented from recovering, especially in forest types characterized by low C/N organic matter (19).

Not surprisingly, the more biomass removed over a given period of time and the greater its nutrient content, the greater the probability that rates of nutrient export will exceed rates of input through natural processes. Short rotations combined with practices that remove a high proportion of site biomass result in exceedingly large nutrient drains. By far the largest losses of nutrients and either present or future soil carbon are associated with harvesting tree crowns and site preparation (81). Various studies show that removing crowns, which have relatively high nutrient concentration, increases nutrient loss by 50% to 400% over harvesting boles only (21, 87, 97, 149).

Throughout North America, sites are often prepared for planting by either windrowing or burning residues in place ("broadcast burning"). Windrowing as traditionally practiced compacts soils and removes large amounts of SOM and nutrients; Morris et al (108) estimated nutrient losses during windrowing as equal to six bolewood harvests. Hot broadcast burns, once the norm in western North America, volatilize large amounts of carbon and nitrogen (81).

Reductions in SOM and soil pore space (the latter due to compaction) are a significant concern (129). Soil organic matter (SOM)—including humus, forest floor, and both fine and coarse woody debris—stores nutrients (especially nitrogen), provides cation exchange and water-holding capacity, and serves as substrate for the belowground food chain; hence SOM is a keystone resource for numerous soil functions. SOM falls into two broad groups that differ both functionally and with respect to potential management impacts. Fine litter (foliage, small branches, epiphytes) in various stages of decay forms the majority of surface organic layers and (eventually) humus within the soil profile, and it functions in nutrient cycling, cation exchange capacity, and water retention.

Coarse debris (logs and large branches) is abundant in natural forests and functions as sites for N fixation, water reservoirs (decayed logs are sponge-like in their ability to retain water), and habitat for numerous fungi, invertebrates, and vertebrates such as salamanders, which are at the top of the soil food chain (62, 71). Immediate impacts of forest management on soil C are mainly associated with extreme site preparation techniques such as hot fires, windrowing, and tilling (70, 81), whereas practices that remove sources of future soil C (trees and litter layers) have longer-term effects that remain to be determined. Presumably losses in those components of soil C that derive from fine litter will be replenished so long as plant communities regrow vigorously, a condition tied in a self-referential loop to the status of soil nutrients, soil C, and soil biology after harvest. Components of soil C derived from large debris—especially tree boles—are more problematic. Until recently, forestry never considered leaving tree boles on site; in fact—quite the opposite—doing so was seen as waste. As I discuss later, retaining trees on site as future sources of large dead wood is a major component of new silvicultural approaches. However, the question of how many trees to leave turns on gaining a better understanding of the functions of large dead wood within the ecosystem.

Though soil biology is undoubtedly the key to understanding soil function (124, 138), the enormous diversity belowground has made research into functional aspects slow and expensive. Consequently, the science of the belowground is in its infancy. Existing studies related to forestry have focused either on total microbial biomass, particularly as nutrient sinks following harvest (27, 169), or on specific functional guilds such as mycorrhizal fungi, nitrogen-fixing and other rhizosphere bacteria, invertebrates, or some combination of these (e.g. 5, 7, 69, 71, 84, 105, 121, 122). Soil bacteria act as important nutrient sinks following clear-cutting, a phenomenon tied to the availability of labile C and therefore likely to be impacted by intensive site preparation (169). Management effects on specific guilds range from minor to severe, depending on the management practice employed and the guild of organisms studied. Significant change in soil biology as a result of clear-cutting and site preparation is always found, including increased bacterial relative to fungal biomass, greater rates of nitrification, reduced concentrations of microbially produced iron chelators, shifts in mycorrhizal types, and sharp declines in invertebrate numbers. However, interpretation is complicated by poor understanding of functional and dynamic aspects of the belowground ecosystem.

Translating impacts on soils to longer-term soil fertility, tree growth, and other ecosystem processes is not always straightforward. Nutrient inputs in precipitation are reasonably well known, but inputs from weathering—the major natural source of all essential elements except N, C, and O—are difficult to measure and poorly understood (31). Moreover, recent research shows conifers (and probably other non-nodulated trees) have some capacity to renew soil fertility. Bacteria associated with conifer rhizospheres and mycorrhizal fungi can fix appreciable amounts of N (17, 94). Both ectomycorrhizal fungi and rhizosphere bacteria significantly accelerate rock weathering and are likely to speed recovery of fertility in soils with unweathered rock in the rooting zone (18, 83). [Soils in the northern United States and Canada contain abundant unweathered rock, but that is not the case with some old soils in the southern United States (107).]

Better understanding the capacity of trees and their symbionts to renew soil fertility, and how that varies with site, species, and environmental conditions, promises to add a significant new dimension to our picture of ecosystem nutrient budgets. A key question that has received little research is whether site impacts can disrupt these biologically mediated renewal processes. The few studies that do exist suggest the renewal process can be influenced by management. N fixation associated with Douglas-fir and its mycorrhizae is stimulated by proximity to certain hardwood species (8), suggesting that in systems where that relationship occurs, excessive vegetation control will reduce associative N fixation. N fixation in ponderosa pine rhizospheres is depressed in both clear-cuts and patch-cuts ($<$0.2 ha) relative to undisturbed forest (79).

Predicting long-term impacts on soil fertility has been further complicated by the fact that pines, in particular, often grow better during their early years on sites that have been intensively prepared than on sites that have not (23). Although the ability of trees to renew fertility may be a partial explanation, most researchers agree better growth on intensively prepared sites is a transitory phenomenon due to various factors, especially reduced competition from herbs and grasses (23, 106, 129). As plantations have reached crown closure, relatively poor growth on intensively prepared sites has become widely evident (20, 33, 43, 128). In one of the few studies in which trees were approaching rotation age, stem volume per hectare of 31-year-old loblolly pine was 23% lower on plots that had been windrowed prior to planting than on plots that had been broadcast burned (43).

The multirotation predictions required for assessments of sustainability, coupled with the complexity and nonlinearity of forest resilience, require experiments and models based in ecosystem-level processes (89, 152). Several models exist that link nutrients (mainly nitrogen) to tree growth (1, 86, 112, 116). Although the importance of such models is clear, they are also potential traps because their long-term predictions cannot be validated in the short term, and there is a history of managers using models as substitutes for observation and critical thought. Yarie (178) compared two models and found they predicted different outcomes for the same management practices. He concluded "... neither (should) be used as a ... decision tool without the help of sufficient expertise in ecosystem ecology to correctly interpret the results."

Several long-term experiments dealing with management impacts on soils and tree growth have been installed within the past few years, each nearly unique in approach and objectives. Now 14 years old, a study installed by the North Carolina State University Nutrition Co-operative manipulated levels of harvest, site preparation, and vegetation control factorially (112). A widely replicated experiment sponsored by the US Forest Service includes different levels of compaction, biomass removal, and vegetation control in a nested design within clearcuts (129). Several studies in the United States and Canada have experimentally manipulated forest structure (via levels of harvest and size of harvest units) and are considering an array of soil chemical and biological variables (6, 46, 76).

Information on potential negative impacts of intensive site preparation has reached field foresters through symposia and other sources. Hot broadcast burns have become less common in the west, and managers in some areas have either abandoned windrowing or adopted windrowing techniques with lower impact. Intensive site preparation is still common, however, at least in part because of faith in the remedial effects of fertilizers. A central challenge for research is to determine the degree to which that faith is justified.

Water

Forests are keystone modulators of the water cycle; hence forestry and water are inseparable. Reflecting that fact, watershed protection was a primary rationale for the creation of the National Forest System, and hydrologic research by the USFS dates back at least 50 years. By the mid-1960s approximately 150 gaged, forested watersheds existed in the United States, many of which involved managed and unmanaged pairs (78). Other studies have either followed single basins as they are harvested over time, or, particularly in the case of large basins, compared data among basins operationally harvested to different levels (e.g. 82).

Hydrology exemplifies many other issues in forest science—large scale and high background variability (temporally and spatially) make generalizations that are both broad and accurate extremely difficult, expensive, and in some cases impossible. Only dramatic impacts on stream hydrology are statistically detectable in short-term studies. Moreover, effects of clear-cutting on stream hydrology tend to be highly variable for various reasons, including bedrock geology, topography, climate (e.g. rain or snow dominated, importance of fog-drip from canopies), and harvest practices. Clearest effects are from experimentally paired, small watersheds, and the ability to detect effects diminishes as one scales up to larger basins (133). Decades-long records are often necessary to discern trends, especially in larger basins.

Small watershed studies generally show clear-cutting increases water yield, though in areas with significant fog-drip (water raked from clouds or fog by tree crowns), yields may decline following harvest (133). Peak flows, which are of more concern environmentally and economically, are often increased by clear-cutting, though that depends on various factors, particularly the extent and rate of logging within a basin, how logging is done, and the road network. Intensive site preparation, vegetation control, extensive roading (especially when poorly designed), and disruption of riparian forests have the greatest likelihood of increasing the magnitude and duration of peak flows (133).

Studies in western Oregon show that clear-cutting and roads act synergistically to alter hydrology. Clear-cutting reduces evapotranspiration (ET) and increases snow accumulation and melt, resulting in increased deep soil water storage that persists until leaf area of deep-rooted trees and shrubs has fully recovered (on the order of decades) (64). In poorly drained areas, water tables rise in clear-cuts (23), and in some cases bog formation can be triggered (DA Perry, personal observation). Roads, on the other hand, alter hillslope flows by converting subsurface to surface flow; hence they provide pathways for deep soil water to reach the surface and flow rapidly to streams (63). On the HJ Andrews Experimental Forest (HJA) (Oregon Cascades), peak flows did not differ between a watershed that was 100% clear-cut without roads and one that was 25% clear-cut with roads, though seasonality of altered flows did differ (82). In both, average peak discharge increased by $>$50% (compared with pretreatment) for the first 5 years after treatment; 25 years after treatment, discharge remained 25% to 40% higher than pretreatment peak flows.

Large basins are a particular challenge because experimental controls do not exist and also because even dramatic events in small watersheds may be statistically undetectable at larger scales without many years of record (133). In the west, records are just now becoming sufficiently long to allow trends to be separated from noise in larger basins. Jones & Grant (82) examined 50-to-55-year records from three pairs of 60- to 600-km^2 basins in the western Cascades of Oregon (paired based on proximity and different rates of logging). Responses in all cases were statistically significant (though with low r^2): a 5% difference in cumulative area clear-cut translated to a difference in yearly peak flows ranging from 10% to 55%, depending on basin-pair. None of the basins were heavily clear-cut (maximum 25% of total basin area), yet Jones & Grant estimate that peak discharges in these basins have increased by 50% to 250% compared with prelogging. The extensive road network required where clear-cuts are in a dispersed patchwork, as is common on federal forests, means total cutover area significantly underestimates potential impacts on hydrology and on spatially mediated processes in general.

Effects of forest management on sedimentation have been easier to demonstrate than effects on water flows because background variability is much less; very little soil is eroded from undisturbed forests. As with water, the best documented studies have been in experimental watersheds, although clear evidence exists from other sources, such as comparisons of logged and unlogged watersheds and historical observations. Sediments associated with forestry come from four primary sources (159): surface erosion from roads, surface erosion from clear-cuts, mass transport during slash burns, and landslides associated with either roads or clear-cuts. Studies on the HJ Andrews Experimental Forest (HJA) found that landslides, especially from poorly designed roads during major storms, pulsed large amounts of sediment in brief episodes, while surface erosion from roads and clear-cuts was more chronic. Eleven years after treatment, suspended sediment from a roaded watershed, 25% clear-cut and burned, averaged 57 times higher (per year) than the unroaded, unlogged control watershed, whereas nine years after treatment, sediment from an unroaded watershed, 100% clear-cut and broadcast-burned, averaged 23 times higher than its control (159). Total increases in surface erosion following clear-cutting are most severe on steep slopes (generally $>60\%$); however, proportional increases may be more severe on shallow slopes (159). Broadcast burning greatly exacerbates losses in both cases. Absolute losses vary widely depending on soil and rock type.

As with many issues in forestry, short-term studies may not be adequate to determine effects on sedimentation. Zeimer et al (179, 180) modeled the long-term cumulative effects of harvesting on sedimentation for coastal northern California to central Oregon (an area with high landslide potential). Their simulations predicted that sediment produced during the first century following harvest would be initially stored in small tributaries, to be washed into larger streams during the second century. That prediction was supported by data from Casper Creek in northern California, which is still adjusting to logging-related sedimentation from the late nineteenth and early twentieth centuries.

Diversity and Habitat

Intensive forestry significantly alters the spatial and temporal structure of forests and, applied widely, of forested landscapes. Aside from the fact that living trees are killed, it has little ecological similarity to natural disturbances, which leave a plethora of structural legacies and usually have a frequency distribution characterized by many small and few large events, hence leave a more variable patch mosaic than does intensive forestry (109, 143, 154). Stand reconstructions show that forest types once believed to be extensively even-aged due to infrequent, large natural disturbances are actually mosaics of age classes resulting from relatively frequent, small disturbances that established cohorts of young trees within a matrix of older trees (42, 47, 160). Because of their biological legacies and spatial patchiness, natural disturbances are likely to initiate different early successional patterns than does intensive forestry, which aims for rapid site capture by even-aged crop trees.

Fire exclusion, which along with roading is traditionally the first step in bringing a forested landscape under management, has significantly altered forest types with a history of frequent, low-intensity fires, especially ponderosa pine in the west and longleaf pine in the south, leading in many cases to increased problems with insect pests and pathogens, and paradoxically to a greater risk of catastrophic fires. Roads may affect diversity in a number of ways, principally as barriers to movement and by providing access for predators (including humans), noxious weeds, and pathogens (123, 148). Various studies have shown that population sizes of bears, wolves, moose, and mountain lions are inversely proportional to road density (e.g. 22).

In short, forestry as commonly practiced places a radically new selective filter on the landscape, structurally much simplified compared to the natural, but also with new elements. Some species benefit, others are endangered, some may adapt. But none has evolved with that filter. The most vulnerable habitats in an intensive forestry regime are associated with forests older than harvest age (20 to 100 years depending on forest type and product), hardwoods (as most forestry focuses on conifers), riparian zones, wetlands, and streams, all of which are unique and biologically rich. In some cases, conifers of one species are replaced by others with faster initial growth; such is the case with longleaf pine in the south, which is often converted to loblolly and slash pines (113).

There is no doubt that many species lose habitat in intensively managed forest landscapes, though it should be borne in mind that habitat has never been a priority on the majority of industrial lands (there are notable exceptions) and has only recently become so on public lands. To most foresters, trees past their peak of growth are like savings bonds that no longer earn adequate interest; not cashing in and replacing with higher-yielding young stands makes no economic sense. The biological trade-offs involved in maximizing economic efficiency are now known to be severe. Research beginning with the International Biological Program (IBP) in the 1960s showed that forests past the peak of growth enter their biological prime, a period characterized by uniquely rich habitat (7, 47, 98). Riparian zones and wetlands are also biologically rich and functionally important (56, 90, 162), and road building, logging, and grazing within riparian zones have been major factors in the widespread decline of both migratory and resident fish in the northwest (100). In some areas, such as the southern United States, wetlands may be drained to plant commercial forests. A number of states and provinces now restrict logging and roading in riparian zones and near wetlands.

The standard approach to conserving diversity in forests has been to establish reserves, resulting in landscapes parceled out among two very different uses: intensive forestry and no forestry. The importance of reserves to conservation is clear. However, in most forested regions, the existing reserve network falls far short of that needed to adequately protect regional diversity (113), and many scientists agree successful conservation will require viewing landscapes for what they are—functional totalities in which both reserves and managed lands play a role (45, 59, 65, 140). The implications of that view have been profound for forestry, as maintaining habitat becomes a central issue in management rather than something to be dealt with "elsewhere." This strategy is not without controversy. Most conservation ecologists agree that the amount of land likely to be set aside will not, by itself, protect sensitive species. However, there are concerns that unproven and possibly ineffectual changes in forestry practices will be used to justify reduced commitment to reserves. The major scientific challenges involve three levels of understanding: (*a*) the relationship between managed forest structure and ecological function at the stand scale; (*b*) spatial patterning of stand structures that meet diversity goals for a given bioregion; and (*c*) the temporal dynamics of stand and landscape structures resulting from natural disturbance, anthropogenic disturbance, and interactions between natural and anthropogenic disturbances (which, as I discuss later, can be significant).

Research on how forestry might be adapted to better protect biological diversity did not begin in earnest until the 1970s. Until that time, habitat concerns on public forest lands focused largely on game animals, which were believed to benefit from the open areas and edge created by patchwork clear-cutting. Eventually, concerns about the impacts of forestry on native diversity led to passage of the National Forest Management Act of 1976 (NFMA), which directed the USFS to seek scientific advice on how to maintain diversity of plants and animals on lands under their jurisdiction. By the time NFMA was passed, US Forest Service biologists had already begun to deal with the issue of nongame bird habitat by hosting a National Symposium (150) followed by four regional symposia. Similar symposia since have dealt with amphibians, reptiles, small mammals, marten, fisher, wolverine, and lynx. In 1979, a group of USFS and BLM wildlife biologists published what came to be known as the "Blue Mountain Book" (because it dealt with the Blue Mountains of eastern Oregon and Washington), a guide for maintaining terrestrial habitat in managed forests (162). The first of its kind, the Blue Mountain Book was in demand throughout the world, and similar guides for other regions soon followed. FEMAT, the plan to protect old-growth associates and fish in the range of the northern spotted owl, relied mostly on reserves (41) [wildlife biologists on the Forest Ecosystem Management Assessment Team (FEMAT) were very wary of unproven silvicultural techniques]. However, 10 large (37,000 to 140,000 ha) Adaptive Management Areas (AMAs) were set aside to experiment with innovative management techniques.

Evidence from the northwest indicates that many species associated with old growth also occur in younger stands that originate from natural disturbances, presumably because of the rich structural legacies left behind in the form of large dead wood, remnant green trees, and sprouting shrubs (58, 60). Large dead wood (snags and logs) provides habitat for numerous terrestrial species, a fact that almost certainly holds for all forest types (62). Logs are also critically important in creating fish habitat because they dam streams to create pools (99, 139).

With the growing awareness of the needs of cavity-users in the late 1970s, federal foresters began leaving scattered trees in clear-cuts (when permitted by state safety inspectors), though dead wood on the ground was still routinely cleared (often because of concerns about wildfire). In the mid-1980s, researchers and managers on the HJA and the Williamette National Forest installed several trials using silvicultural techniques intended to capture the diversity of naturally disturbed forests. Initially termed "new forestry," and now "variable retention harvest," the basic idea is to leave a certain number of large, green trees at harvest, either dispersed or aggregated, with the objective of providing at least three functions not found in intensively managed forests: habitat continuity for species requiring large, green trees; a diversity of age classes with concomitant vertical and/or horizontal heterogeneity; and future sources of large dead wood (46). At least two companies have since initiated operational retention harvests (46, 158). Several replicated experiments are now installed in the United States and Canada that manipulate retention levels and, in at least one case, the physical arrangement of retention (6, 46, 76). These incorporate a level of biological detail far beyond anything in previous silvicultural experiments, including measurements of small mammals, birds, invertebrates, plants, and microbes.

Results to date (including studies conducted in earlier trials) show that young stands with remnant old trees support significantly greater abundance of some old-growth associates than do young stands without old remnants, including some not found at all in young stands without old trees (25, 60, 117, 137). Simulation predicts that bird richness will remain higher in mixtures of old and young trees than in stands composed only of young trees for 140 years following harvest (61). However, not all birds associated with old growth benefit from leaving residual trees, and some that do benefit exhibit threshold responses in which relatively small changes in the density of older trees have large effects on abundance (60). Research on this issue is in its infancy, and it would be surprising if new patterns did not emerge with time.

Resistance to Disturbances

> A vast experiment is underway. Its unplanned and unwitting design is changing the spatial and temporal structure of terrestrial ecosystem... R. L. Burgess and D. M. Sharp (24)

Insights gained with the emergence of landscape ecology and conservation biology as disciplines over the past two decades leave little doubt that the "vast experiment" to which Burgess & Sharp refer to in the above quotation has significantly perturbed the fabric of species relationships and ecological processes within regions, with largely unpredictable consequences that may take decades or centuries to unfold (85, 123, 163). Infestations of trees by a number of native pathogens and defoliating insects are already outside of known historic ranges in regions where humans have significantly altered forested landscapes, including the western spruce budworm, Swiss needle cast, and several root rots in western North America; fusiform rust and southern pine beetle in the south; and eastern spruce budworm and ash yellows (a viral disease) in the northeast United States and eastern Canada (26, 123, 127, 136, 173). Widespread changes in stand structure have also increased susceptibility of forests throughout the west to high-intensity crown fires (2).

Consistent with the resource concentration hypothesis of herbivore/pathogen dynamics, epidemics of recent years are frequently related to the spread of host trees. The spread of hosts stems in turn from various factors that depend on locale but all involve changes in the historic disturbance regime. In the south, agriculture, forestry, and fire exclusion have combined to sharply reduce the extent of once widespread longleaf pine forests. Much of that area has been planted with slash and loblolly pines, which have faster early growth than longleaf (hence are favored by foresters) but are also more susceptible to fusiform rust and southern pine beetle (127, 136). In the interior western United States, southern British Columbia, northeast United States, and eastern Canada, logging old growth coupled with fire exclusion allowed the spread of *Abies* sp., principle hosts for spruce budworm (118, 173). An ongoing epidemic of Swiss needle cast in the coastal mountains of Oregon is believed to have been triggered by the large areas of young Douglas-fir plantations (G Filip, personal communication). (Note, these are all native insects and pathogens—exotics are another story.)

Depending on the particular situation, various other factors are believed to have contributed to pest outbreaks. Roads have clearly accelerated the spread of several diseases in the Pacific Northwest (123). Disruption of the natural enemy complex through habitat loss and (in some cases) pesticides may be involved in outbreaks of herbivorous insects (137, 165), though that is difficult to demonstrate conclusively. The incidence of fusiform rust on southern pines increases with management intensity, particularly weed control (181) and fertilization (127). Eliminating broadleaved species from plantations also results in greater incidence of root rots on Douglas-fir (146) and defoliators on white spruce (52), phenomena that could stem from greater concentration of food plants (conifers), disruption of natural enemies that depend on broadleaved plants for habitat, or both.

Genetic and ecologic strategies have been employed to deal with herbivorous insects and pathogens in forestry. Selection for resistance has significantly reduced incidence of fusiform rust in southern pines (74); whether this is an evolutionarily stable situation remains to be seen. Experiments on the stability of resistance in slash pine indicate a highly dynamic relationship between pathogen and host, with significant interactions between tree genotypes and both environment (including the pathogen) and time (RA Schmidt, personal communication). A single gene having major control of fusiform resistance has been identified in loblolly pine (175), a situation in which rapid evolution of the pathogen would be expected.

Ecologic strategies center on diversifying landscapes and promoting habitat for natural enemies. Evidence from deliberate introductions of biotic control agents strongly supports the importance of natural enemies as an effective, and perhaps evolutionarily stable, source of control (77), and a great deal of spatially explicit modeling points to the importance of landscape patterns in host-pest dynamics (85). Ecologic approaches have so far been utilized mostly in European forestry, though concepts of integrated pest management are gaining a foothold in North American forestry.

THE FUTURE

> There is one outstandingly important fact regarding Spaceship Earth, and that is that no instruction book came with it.
>
> Buckminster Fuller (50)

The scientific challenges facing forestry are precisely those confronting basic ecology: better understanding the relationships among structure, function, and spatiotemporal dynamics of systems interconnected at many scales; and coping with the "certain uncertainty" inherent in complex systems. Forest management alters forest structure and thereby influences processes, some purposely, as with productivity, some inadvertantly, as with erosion, population dynamics, and susceptibility to disturbances. How much can the structure, hence processes, of complex ecological systems be altered without compromising long-term integrity, or, to turn that question on its head, how much structure must be retained to maintain integrity? Can technology successfully substitute for nature's evolved controls? Implicit within these questions are numerous others having to do with system states and measureable variables that tell something useful about future system states.

During the 1990s a set of philosophies and general principles emerged under the rubric of ecosystem management (EM). During its short life EM has generated numerous papers and symposia, most of which share common themes: sustainability as the overall guiding principle; explicit goals; recognizing interconnections; working across ownerships; taking a broad view spatially and temporally; recognizing that ecological systems are dynamic but that some changes have greater long-term consequences than others; accommodating human needs within the constraints of ecological objectives (29, 57). The real challenges lie in translating abstract principles to what is (or is not) done on the ground, and developing tools to assess whether goals are being achieved.

Several strategies have been or are being used to translate the general principles of EM to specific practices. In most cases these were developed simultaneously over the past decade and are largely complementary rather than competing. The approach exemplified by FEMAT (41) focuses largely on reserves and their interconnectance. In FEMAT, the spotted owl serves as an umbrella species whose protection is hypothesized to de facto protect other OG associates, and monitoring protocols are established to test that hypothesis. FEMAT required relatively few modifications of forest practices in the managed matrix (which under the plan composed a minority of the landscape in many areas), though it took the ground-breaking step of devoting large areas specifically to experimentation and learning, and it set the important precedent of assembling multidisciplinary teams, along with protocols for synthesizing sometimes widely divergent opinions about the probable outcomes of different management scenarios.

A second approach, whose roots lie in the IBP-funded studies of OG coniferous forests and the emergence of landscape ecology as a discipline, deals primarily with how lands outside of reserves are managed and uses historic patterns of disturbance and recovery as templates for management. At the stand level, this has led to techniques for protecting biological legacies, particularly the variable retention harvests discussed earlier, and stimulated movement toward longer rotations (35), the latter a strategy adopted by the Germans 30 years previously. At the landscape level, the concept of natural range of variability (NV) has received considerable attention. NV uses historic patterns of disturbance to guide harvesting patterns, as, for example, identifying areas best suited for longer rotations or small patch cuts and areas where shorter rotations or larger cuts would be appropriate (30, 91). A third approach also focuses on managed lands but uses functional models rather than historic. A good example is Hansen et al (59), who used life histories to predict landscape patterns required to maintain habitats for a suite of vertebrate species.

Each strategy has strengths and weaknesses. I discussed issues surrounding dependence on reserves earlier. NV has had the positive effect of making foresters think about history (reliably determining history is another matter); however, taken too literally the approach promotes the false belief that logging can fit within a “natural” range of variability. Logging of any kind—whether clear-cut or single-tree selection—is an unnatural event in the history of a forest, and the relevant scientific question is not whether a practice fits within NV, but how far management can depart from NV before compromising system integrity. Answering that question requires a functional approach that deals with the suite of processes underpinning integrity, which in turn requires a measureable definition of integrity, testable hypotheses concerning keystone processes and their links to system structure, and protocols for choosing among hypotheses when the systems of interest are highly dynamic in space and time and the information base is weak (e.g. 75). To date, ecological processes such as disturbance, hydrology, and nutrient cycling have seldom been integrated with habitat in EM models (the integrity of soils is virtually never mentioned in the EM literature), though that is beginning to change (115, 151).

The move toward ecosystem management by federal agencies may have little relevance for forestry as a whole in the United States, where by far the greatest amount of timber is produced on private lands. In 1991, for example, 32% of timber harvested in the United States was from industry lands and 51% from nonindustrial private lands (167). As in agriculture, maximizing profit in forestry is most often associated with simplifying systems rather than creating or maintaining diversity (the degree to which the green certification movement changes that equation remains to be seen). However, while diversity may not be an explicit goal on most industrial lands, sustaining the productive base is, which leads directly to questions concerning the functions of diversity. A growing number of ecologists believe that complexity and stability of ecosystems are positively linked (where stability refers to ecological functions and potentials rather than species composition on a given piece of ground) (28, 36, 125); however, the nature of the linkages is poorly understood and "very few models . . . incorporate biological complexity as a regulating component of ecosystem function" (138). Maintaining genetic diversity within expansive areas of high-yielding cultivars shifts what in the natural forest was likely to have been a complex set of genetic, species, and landscape controls (top down and bottom up) to a much greater reliance on genetics (bottom up), an interesting and important experiment, unfortunately uncontrolled. With the discovery of single gene control over susceptibility to fusiform rust in loblolly pine (and probably slash pine), the stage is set for a classic, some might say mythic, confrontation between the forces of nature and the ingenuity of humans. The rust is likely to evolve relatively quickly around a single gene. Can biotechnologists put enough copies in the field to confound that process?

The forestry of the future seems likely to blend aspects of intensive management and EM, either on the same piece of ground, across landscapes, or (more likely) some combination of the two. What Seymour & Hunter (140) termed the triad approach—a mix of reserves, intensively managed lands, and EM lands—provides a useful starting point. The central issue then becomes one of assessing probabilities of outcomes associated with differing spatial and temporal patterns of the three general land-use types. That requires, in turn, improved understanding of structure-process-function at the scale of landscapes (e.g. habitat, disturbance) and sites (e.g. resilience following harvest or natural disturbance).

Science is faced with the challenge of providing knowledge that helps society achieve sustainability (96). Numerous scientists have concluded this can only be accomplished if we begin to grapple successfully with complexity (e.g. 34, 95, 119), a strategy that radically departs from the industrial approach of simplifying systems to make them more predictable. But coming to grips with complex reality requires more than change in management philosophies; some fundamental approaches of science and the role of scientists in society must be reassessed as well. The idea that ecological systems are quintessential complex systems is old; however, much knowledge concerning the characteristics of complex systems is new and growing. Though much of this knowledge has come from physicochemical systems and their models, ecological systems share many characteristics with these: existence far from thermodynamic equilibrium, interconnections through positive and negative feedbacks, self-organizing dynamics, metastability and vulnerability to threshold transitions (124, 166). Adding the social and economic dimensions defines the stage on which forestry plays and greatly magnifies the complexity.

Assessing how much such systems can be altered without triggering unforeseen consequences is far from straightforward. Some changes are obvious, others subtle; some set processes in motion that may not manifest for decades or centuries. Some, perhaps many, changes in system structure alter probabilities rather than being distinctly causal, as when susceptibility to herbivores, pathogens, fire, or wind is increased or decreased. Whether stands so altered actually burn down or are eaten up depends on factors such as climate, the evolutionary interplay between hosts and pests, and diverse biotic controls with complex spatial and temporal dependence. The logic of cause and effect has limited utility in such a milieu.

Scientists have played a much expanded role in forestry in the 1990s, a trend that will almost certainly continue. The traditional routes of experiment and modeling remain vital, and, despite inadequate funding (at least in the United States; 114), there are presently far more experiments dealing with links between structure and process in managed forests of the United States and Canada than at any time in the past. Within the scope of traditional science, however, issues of experimental analysis and data interpretation need to be dealt with, especially the obsession with “significance questing”, which, as Rothman pointed out with regard to the medical sciences, and which is equally true for natural resources sciences, “has become for some a clumsy substitute for thought” (134). When the quest is for significance at very high levels, as is the norm, the burden placed on establishing differences among management approaches effectively favors implementing those with the highest economic payoff. Various scientists have argued that the burden of proof needs to be shifted away from practices that would change the management status quo and placed instead on practices that alter systems most dramatically or have the greatest economic payoff (e.g. 34, 72).

Funtowicz & Ravetz (51) argue that situations in which both system uncertainty and decision stakes are high require a "post-normal" or second-order science, which Costanza (34) interprets as taking the scientific method into new territory. "The scientific method," Costanza writes, "does not, in its basic form, imply anything about the precision of results achieved. It does imply a forum of open and free inquiry without preconceived answers or agendas . . . ." Whether one accepts the new arena as science or not, the fact is that scientists are increasingly playing nontraditional roles in resource management. This has taken various forms, including adaptive management, which effectively blurs the boundary between management and experiment (172); various regional scientific assessments (41, 72, 145, 151); expert testimony in courts and before legislative and regulatory bodies; and small teams of scientists that assess the suitability of lands for green certification. "We need a new model," wrote Gordon & Lyons (55), "for linking science, management, and policy . . . ." The circumstances of the past few years have thrust forestry scientists into a leading role in developing that model.

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