PREDICTING LONG-TERM EFFECTS OF SILVICULTURAL PRACTICES ON FOREST SITE PRODUCTIVITY

Phillip Sollins, Joseph E. Means, and Russell Ballard

ABSTRACT: We describe a system for predicting long-term consequences of silvicultural practices, especially those that may decrease long-term forest productivity. The system requires: (1) conceptual models that incorporate current understanding of interactions among ecosystem processes; (2) process studies that, guided by the conceptual models, allow us to establish equations for the transfer of material and energy among ecosystem components and to refine the conceptual models; (3) a management-oriented simulation model, developed from the conceptual model, used to predict long-term consequences of silvicultural practices; and (4) validation studies that test those predictions. Conceptual models must account for interactions among processes as well as for all material flow. Process studies should clarify the relations between processes and their controlling factors; operational trials should duplicate silvicultural practices to determine their effectiveness. In general, process studies should be replicated at each site, operational trials across many sites. Experimental treatments selected for process studies need not adhere to standard silvicultural practice. Development of a management-oriented simulation model must be a high priority. FORCYTE, developed by J. P. Kimmins and K. A. Scoullar, may offer the best starting point for foresters and researchers in the Pacific Northwest. Operational trials should validate the simulation model rather than merely provide information for specific sites, species, and treatments.

INTRODUCTION

Our understanding of how forest ecosystems function has increased greatly in the last 15 years. Nonetheless, although new silvicultural practices have been proposed and implemented, our ability to predict the long-term effects of these practices has increased little.

For example, there is increasing concern that more complete removal of forest biomass during harvest will lead to long-term declines in productivity (Boyle 1976, Boyle et al. 1973, Harvey et al. 1980, Kimmins 1977, Leaf 1979). A decline in second-rotation yield has been demonstrated at sites that were windrowed (Ballard 1978) and slash-burned (Keeves 1966), but such long-term studies are few. An even greater problem is that conceptual models are not adequate for addressing the problem (Morrison and Foster 1979, Stone 1979, Tamm 1979).

We urgently need an efficient way to use existing knowledge of forest ecosystems to predict the long-term impacts of silvicultural practices. For

PHILLIP SOLLINS is a research associate professor, Department of Forest Science, Oregon State University, Corvallis, Oreg. 97331. JOSEPH E. MEANS is a research forester at the Pacific Northwest Forest and Range Experiment Station, 3200 Jefferson Way, Corvallis, Oreg. 97331. RUSSELL BALLARD is department manager, Western Forestry Research, Weyerhaeuser Company, Tacoma, Wash. 98477.

example, the National Forest Management Act requires that the National Forests be managed without "impairment of the productivity of the land" (U.S. Government 1982). Obviously, decisions must be made today based on existing knowledge, and new studies must be initiated as well.

In this paper we describe a system which can help us synthesize information, coordinate research, and utilize existing data to make long-term projections. This system requires four components: conceptual models, process studies, simulation, and validation studies. We define and provide examples of each of these, and show how they can function together as a coordinated system.

CONCEPTUAL MODEL

A conceptual model helps us integrate our understanding of how the forest ecosystem functions. It identifies the important compartments of an ecosystem, the processes by which material and energy are transferred among them, and the relationships among these processes. For example, a conceptual model of forest growth must include the effects of nutrient availability and plant competition (e.g., Linder 1981) as well as the relations between organic matter in the soil and the ability of the soil to supply nutrients to plants (e.g., McGill et al. 1981).

Separate conceptual models may be needed for different subsystems within an ecosystem, such as the forest floor or the tree canopy. But it may be difficult to integrate information about the subsystems without a conceptual model of the entire ecosystem that explicitly shows how such submodels interact.

Conceptual models are often presented as box and arrow diagrams illustrating the transfer of material between compartments (fig. 1). In such material-flow models, an arrow or similar symbol denotes a process and the boxes represent pools of material. These diagrams can easily be converted into quantitative budgets showing the amounts of material transferred along each pathway and changes in pool sizes over a convenient time period such as 1 year (Bormann et al. 1977, Cole et al. 1967, Sollins et al. 1980).

Because the budget accounts for all material flowing through the forest ecosystem, inconsistencies in the data can often be discovered by checking for conservation of mass (Sollins 1982). Ranking the transfers according to the amount of material flowing each year provides an initial estimate of the importance of each process within the ecosystem. Although quantity does not necessarily equate with importance, this procedure offers a useful starting point.

A disadvantage of conceptual models based on material flow is that they cannot easily be used to illustrate interactions among processes.

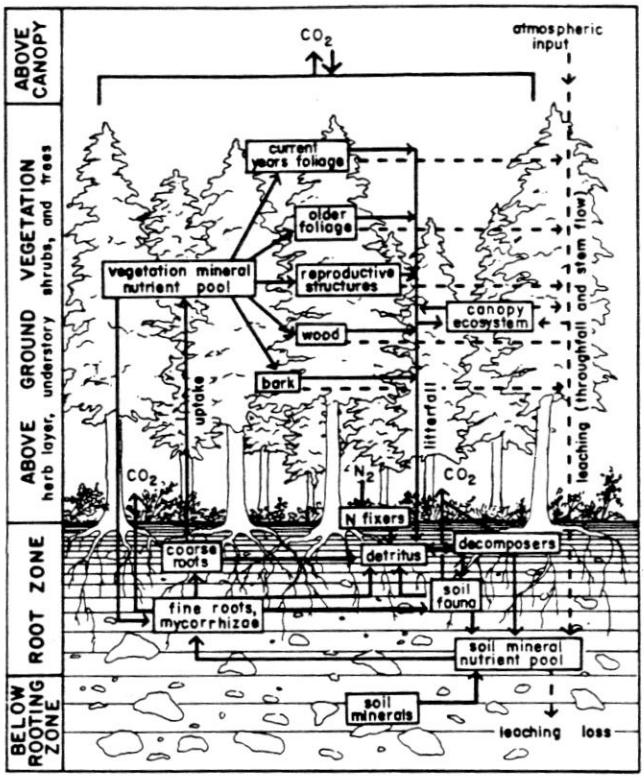

Figure 1.--A conceptual model of material transfer in a coniferous forest (from Johnson et al. 1982).

Although Forrester (1961) proposed a schematic notation for superimposing interactions upon a material-flow diagram, our experience has been that such notation inevitably creates an unintelligible diagram.

Interactions among processes, however, can be represented clearly with diagrams that emphasize the processes rather than the compartments (fig. 2). Word models, written descriptions of interactions among processes (table 1), are also effective. In either, the interactions among processes must be described explicitly. Material-flow diagrams and budgets alone cannot tell the whole story.

Descriptions of interactions, however, can be quite misleading unless they are based on and developed in conjunction with a material-flow budget. Without a material-flow budget, it is too easy to omit an important interaction or process by assuming that we know what is important. Omissions and erroneous assumptions can be corrected, of course, but the trial-and-error approach may prove expensive. First constructing a material-flow budget that accounts for all flow may save considerable effort in the long run.

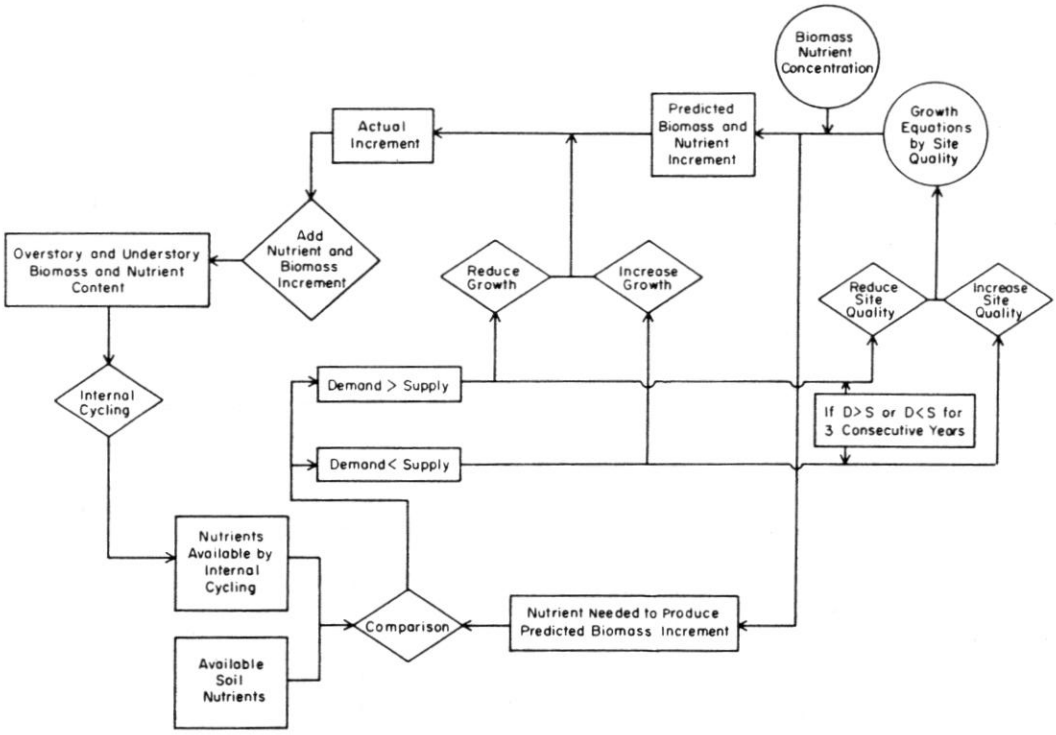

Figure 2.--Diagram showing interactions between nutrient availability and biomass in FORCYTE (from Kimmins and Scoullar 1979).

Table 1--Interactions among modules of CONIFER (from Sollins et al. 1979)

Effect of carbon variables on water and energy flows

A. Foliage biomass affects:
   1. Transpiration
   2. Fraction of rain incident to canopy that strikes foliage, and therefore also fraction striking nonfoliage. (This and following two affect drip, litter, and soil moisture dynamics. There are also indirect effects through percent cover.)
   3. Water retention capacity of canopy
   4. Distribution of retention capacity between foliage and nonfoliage
   5. Fraction of rainfall passing directly to forest floor (through percent cover)
   6. Net longwave radiation input to canopy (through percent cover, which affects input and loss)

B. Stem biomass affects:
   1. Percent cover (and therefore numbers 2-6 above)

C. Fine leaf and woody litter mass affects:
   1. Water retention capacity of litter

Effect of energy variables on carbon and water flows

A. Heat input to canopy affects:
   1. Potential evaporation from canopy
   2. Transpiration

B. Litter temperature affects:
   1. Litter decomposition processes
   2. Potential evaporation from litter

C. Soil temperature affects:
   1. Large and fine root respiration and growth

D. Net heat input to snowpack and heat deficit of snowpack affect:
   1. Net transfer between free water and ice in snowpack

Effect of water variables on carbon and energy flows

A. Soil moisture affects:
   1. New and old foliage photosynthesis (via stomatal resistance)
   2. Fine root death (via plant moisture stress)
   3. Dead root + soil organic matter decomposition processes

B. Litter moisture affects:
   1. Litter decomposition processes

C. Snowpack ice affects:
   1. Litter temperature

D. Snowfall affects:
   1. Heat loss from snowpack due to snowfall
   2. Albedo of snowpack

E. Drip plus direct rainfall affect:
   1. Litter and soil temperature

Table 2--Experimental treatments suitable for process studies

Treatment	Examples of processes affected directly
Trenching (root exclusion)	Uptake, decomposition, respiration
Fertilization	Leaching, decomposition, uptake, nitrification, denitrification
Defoliation	Transpiration, litterfall, light and water interception, photosynthesis
Acidification	Cation exchange, weathering, Fe and Al eluviation
Soil compaction	Water infiltration, soil aeration, surface erosion
Thinning	Photosynthesis, respiration, light and water interception
Devegetation	All heat and water transfers, uptake, decomposition, etc.

PROCESS STUDIES

Process studies, the second component of a systematic approach, attempt to define the relations between each process within the conceptual model and the factors regulating each process. Examples of ecosystem processes include decomposition of foliage litter, N fixation, and photosynthesis. If a conceptual model is built around transfers and accumulation of material and energy, the processes are simply all the flows of material and energy among compartments. Jorgenson et al. (1975) review many of the material-flow processes important in forest ecosystems; Gorham et al. (1979) and McColl and Grigal (1979) describe others.

We have said that process studies attempt to clarify the relations between processes and controlling factors. It is important to separate them from operational trials, which attempt to duplicate a silvicultural management practice to determine its effectiveness. The two have different objectives and therefore different design criteria. An experimental treatment intended to be part of a process study must be designed for easy interpretation of results (table 2). If, for example, litter is to be raked off a plot, then the same amount of litter should be removed everywhere from each plot. To assure uniform treatment, such an experiment is usually conducted by researchers or under their direct supervision. In an operational trial, as in actual management, the amount of vegetation removed, clipped, or sprayed varies greatly within each treatment area. For process studies, however, the treatment needs to be more carefully controlled.

Because most management treatments affect many components of the forest ecosystem simultaneously, such treatments are of limited value in process studies. For example, any site-preparation treatment or harvest method affects the litter layer, the soil, and the vegetation. While it may be easy to identify components that are affected by a management practice, it can be almost impossible to separate cause and effect.

For process studies, then, it is preferable to devise a treatment that affects only one component of a system. Then, when an effect is detected, its cause will be clear. We do not mean, however, to downplay the importance of operational trials. They are critical to the overall research/management process and will be discussed later.

An important feature of any process study is replication. This procedure, however, must be tailored to the researcher's objectives. For instance, by repeating an experiment at many sites, mean and variance can be estimated across a broad range of sites. Such replication, however, gives no estimate of mean or variance at each site, a constraint that may severely limit our ability to extract information about processes. The problem here is that many relations between processes and their controlling factors are nonlinear; for example, a two-fold change in temperature will usually not cause a two-fold change in decomposition rate. Thus, when we try to relate average values for decomposition rates over broad regions to average temperatures over broad regions, we find poor correlations. A single equation can describe the relation (Bunnell et al. 1977a, 1977b), but only if we have a good estimate of the mean temperature and decomposition rate at each site. To obtain site-specific data, measurements and treatments must be replicated at each site. To obtain information applicable to a broad region, studies must be replicated across a wide range of sites. As a rule of thumb, process studies require site-specific information; operational trials require replication across a broad range of sites.

Replication, however, must be approached cautiously. Given deadlines and finite budgets, it will never be possible to measure all processes with the degree of statistical elegance that we might like. To obtain accurate data for one process and ignore other processes entirely may not help, particularly if the process closely studied turns out to be insignificant. An alternative is to first obtain at least some information about all major processes at a site, even if this precludes adequate replication. In poorly defined systems, such as are dealt with in forestry, some initial study of all the processes may be essential. This done, rigorous investigations can begin on those processes that seem to be most important.

In the system we describe here, the object of process studies is to define the factors regulating each process at each site, not to test management strategies. Research objectives should therefore dictate the choice of sites. Experimental forests and Research Natural Areas, such as those operated by the USDA Forest Service and many universities, offer advantages for process research. When research is concentrated at a specific site, the information from one study can be used directly in another without having to account for differences between sites. Baseline meteorological and hydrological data are also frequently available for such sites, increasing the efficiency of process research.

Treatments selected for process studies need not follow standard silvicultural practice or be economically feasible. An excellent example of this is an experiment by Turner (1977) in Douglas-fir stands in western Washington in which N availability was decreased temporarily by adding carbohydrate (sugar) to the forest floor, an expensive and operationally impractical treatment. The C:N ratio of the forest floor was increased markedly, affecting decomposition, leaching of N from the forest floor, and internal redistribution of N within the trees. Occasionally, treatments that adhere to standard practice will prove valuable as part of a process study. If results are monitored for a sufficient time, the treatment can then serve as both an operational trial and a process study.

Simulation models can be important tools for process research. A research-oriented simulation model can be constructed for a selected process or set of processes such as decomposition (Bunnell et al. 1977a, 1977b) or water and energy exchange in forest canopies (Halldin 1979). The output can be compared to the results of process studies in order to verify our understanding of that portion of the system. A sensitivity analysis can be performed on such a model, a procedure in which each parameter value is varied by a fixed percentage in order to see which parameter values influence the process most. Such factors are then obvious candidates for further study.

MANAGEMENT-ORIENTED SIMULATION MODELS

The third component of a systematic approach to predicting forest productivity is simulation. A "management-oriented simulation model," as defined here, is one designed specifically for land managers interested in the long-term effects of silvicultural practices. To be useful, a management model must predict ecosystem behavior over a wide range of environments and time intervals. The model should predict yield, and costs and benefits in terms of both dollars and energy. The model must simulate processes if it is to be extrapolated to combinations of site, species, and treatment outside the experience of its authors. Effects of nutrition must be included. Input requirements and run cost must be kept modest and output format must be convenient or the model will not be used.

A management-oriented simulation model can be developed from the conceptual model once process studies have provided the necessary equations describing each process. Without an adequate conceptual model, progress may be painfully slow and expensive.

Computer simulation is the only way land managers can foresee the behavior of forest ecosystems over many rotations, an interval longer than our life spans. Although projects should be initiated that will span several rotations, we cannot afford to wait for the results. Occasionally, we may find chronosequences of stands that allow us to gather data simultaneously on different stages of natural stand development, but it is difficult to determine how similar the stands were when established (Stone 1975). Moreover, intensive management has only been practiced for a few decades in most forest regions, and few, if any, sites have been managed intensively for several rotations. Thus, although simulation results may be tentative, there are few alternatives.

A good management model allows land managers to select silvicultural alternatives on the basis of the long-term consequences. Most importantly, a good model can help us deal with the problem that each component of the ecosystem is connected to every other--that one cannot be altered without affecting all. For example, fertilization affects many processes simultaneously. In addition to speeding tree growth, it can promote nutrient immobilization by the soil microbiota, increase the rate of litter decomposition, burn roots, and inhibit mycorrhizal development. All of these processes will interact to affect uptake by the trees and their subsequent growth. An adequate description of the effect of fertilizer on tree growth therefore requires a model of the entire system. A computer simulation model can be a practical way to organize such a description, which then becomes a hypothesis for the behavior of the whole system and can be tested by comparing the predicted and observed responses.

A realistic management-oriented simulation model will help research managers to assign research priorities. Through sensitivity analysis, critical processes can be identified and research dollars invested where the need and payoff is likely to be greatest. A model is not a substitute for creative thinking; but to the extent that it reflects our current understanding of the system, it will be a powerful tool for guiding research.

We know of only two management-oriented simulation models for forests that include the effects of nutrient availability. FORTNITE is described by the authors (Aber et al. 1982) as a generalized computer model for organic matter and N dynamics in forest ecosystems. Developed by merging a model of forest floor decomposition (Aber et al. 1978, 1979; Aber and Melillo 1982) and a model of forest succession (Botkin et al. 1972), it treats a 10- x 10-m plot and follows individual trees and age classes of litter through time. Because some processes are assumed to be random, the computer program reports averages over replicate plots. The model has been "parameterized" for a New England hardwood forest and used to predict effects of rotation length, harvest intensity, and fertilization on fiber yield (Aber et al. 1982).

The authors show that it accurately predicts trends in basal area, forest floor biomass, and dead wood mass after clearcutting, although data available for comparison are limited. Using the model, they concluded that extremely short rotations would reduce yield by as much as two thirds, but that fertilization might offset some of the decrease. Whole-tree harvesting on a 90-year rotation yielded more fiber than conventional clearcutting, while selective cutting yielded slightly less.

Hemstrom and Adams (1982) have adapted JABOWA, the forest succession model used in FORTNITE, for use with conifer forests in the Pacific Northwest but have not incorporated the nutrient cycling portion of FORTNITE into their model (V. Dale, personal communication 1983).

The other management-oriented simulation model which includes effects of nutrient availability is FORCYTE (Kimmins and Scoullar 1979). It is designed to predict, on a site-specific basis, the long-term effects that various intensive forest management and harvesting practices may have on nutrient budgets and productivity as well as on energy and economic costs. It uses an input data file to provide the necessary site- and species-specific information and to specify the regeneration, spacing, thinning, fertilization, and harvesting options for each rotation. Many basic ecosystem processes are included in the model (fig. 2). Tree growth is predicted from information on yield in managed and unmanaged stands (see, for example, Hann and Riitters 1982). It is assumed that tree growth will decrease from these measured rates if levels of available N are not sufficient to meet growth demands. The effects of moisture availability are included implicitly by recognizing three site classes labeled good, medium, and poor. A site can change from one site quality class to another in response to proper (or improper) management. Early versions of this model were designed for even-aged, single-species forests managed on rotations of less than 150 years; but the model can be adapted to other stand structures and forest types. As of 1983, FORCYTE had been used for 4 years as a teaching tool at the University of British Columbia and at Oregon State University. It was also being modified for use with western hemlock in the Oregon Coast Range, subtropical *Eucalyptus* plantations in Brazil, black spruce in Alaska, radiata pine in South Australia, and several other forest types.

Both FORTNITE and FORCYTE incorporate most of the information on nutrition and productivity available in the regions for which they were designed. Both models, however, have limitations. Neither has yet been validated adequately against independent data. But with refinement and more validation, both could become valuable management tools in their respective regions.

VALIDATION STUDIES

Under validation, the fourth component needed to predict long-term productivity, we include any procedure by which we increase our confidence in the correctness of a model. This depends on the similarities between observed and predicted responses, the number of model variables checked, the treatments involved, and the length of time, range of sites and climatic conditions over which comparisons are made. Validation studies must eventually span two or three rotations if long-term predictions of the model are to be verified.

To be meaningful, validation studies must compare model predictions with experimental data that were not used to construct the model. Once the current version of the model has been validated, the results of the study can be used to construct a refined version. A new, independent set of data is then needed to validate this refined model.

Operational trials can play a critical role in the validation process. Such trials allow us to test many parts of the model at once because they affect various ecosystem processes simultaneously. Note that this is precisely the reason why we suggested that most operational trials are not suited for process studies.

Extensive operational trials, conducted by industry and agencies, already cover a wide range of sites and treatments (table 3). Because the data have already been collected, such studies can be used to validate the model at an extremely low cost. All too often, the data from operational trials are used only to provide information on the effects of a particular silvicultural practice at a particular site or set of sites. Their value increases if they are used to validate a model that can then be extrapolated to other sites and silvicultural treatments and through time.

Many studies not generally considered operational trials may also serve to validate management-oriented models. Several long-term studies of effects of insects, animal activity, and disease on growth and yield (table 3) could be particularly valuable because they include processes and interactions seldom addressed in silvicultural trials. For example, if disease or severe damage by insects or other animals is noted during a fertilizer trial, measurements are sometimes discontinued on the affected plots. Such action may be understandable because the object of the study was to gauge fertilizer response. But insects and disease are important components of the forest ecosystem and have considerable impact on yield; including such interactions in a model and validating it accordingly will increase its usefulness as a management tool.

Operational trials, too, will be more useful for model validation if key ecosystem processes and pools are monitored, not just the amount of biomass removed. The measured processes should be those that sensitivity analyses have shown will have a critical effect on the accuracy of the predictions.

Such monitoring can provide two important benefits. First, weak parts of the conceptual model can be identified and then improved with process studies. Second, the process data can provide an additional check on the validity of the underlying conceptual model. For example, it is conceivable that a management model could predict yield

Table 3--Operational trials and other experiments suitable for validating models of long-term productivity

Treatment	Example	Reference[1/]
Fertilization	Northwest Regional Forest Fertilization Project	(1)
Levels of utilization (harvesting intensity)	Department of Energy study at Pack Forest and elsewhere	(2)
Multiple rotations	Long-term CFI plots in southern Australia already spanning several rotations	(3)
Thinning	Levels of Growing Stock Study in Pacific Northwest	(4)
Sludge application	University of Washington/Metro Study	(5)
Vegetation control	CRAFTS Project	(6)
Mixed species plantings	Alder/Douglas-fir mixes at Wind River and Cascade Head; Oregon State University LTER study on Douglas-fir/Ceanothus mixes	(7)
Insect control	Effects of levels of tussock moth defoliation on Douglas-fir growth	(8)
Animal damage	Animal damage impacts on conifer plantations	(9)
Disease	Levels of *Dothistroma pini* control	(10)
Irrigation	SWECON (in combination with fertilization and insect control)	(11)
Site/residue treatment	Pacific Northwest residue treatment studies	(12)
Fire	Prescribed burning in southeastern U.S.A.	(13)
Soil removal	Soil removal during site preparation	(14)
Drainage	Drainage intensity, southeastern U.S.A., coastal plain	(15)

1/ (1) Peterson and Gessel 1983
(2) Cole and Bigger 1983
(3) Keeves 1966
(4) Williamson 1976
(5) Edmonds and Cole 1980
(6) Preest 1975
(7) Miller and Murray 1978
(8) Wickman 1963
(9) Black et al. 1979
(10) Gilmour and Noorderhaven 1971
(11) Aronsson and Tamm 1982
(12) Cramer 1974
(13) Stone 1971
(14) Glass 1976
(15) Terry and Hughes 1978

correctly on occasion yet still be substantially incorrect in its representation of internal processes. A model that accurately predicts rates of such processes *and* crop yield is much more likely to be correct in a wide range of circumstances.

Long-term growth and yield plots deserve special mention. The Pacific Northwest has an unusually large number of these with records spanning up to 48 years and areas as large as 42 ha (Sollins 1982, Williamson 1976). Additional plots have been established by the USDA Forest Service that, if maintained over the next few decades, will provide comparable information (Hawk et al. 1978). These plots offer our only opportunity to check model predictions over long periods of time through the use of records of tree growth and mortality. They also give us the only opportunity to conduct process research at sites for which such records are available. Consequently, these plots must be protected. Buffers must be maintained because clearcutting to the edge of the plots will inevitably increase mortality within them. Salvage operations within the plots also must be prevented if forest floor and soil processes are to be studied.

INTEGRATING THE FOUR COMPONENTS

The overall object of the system described here is to increase our understanding of forest ecosystems (the conceptual model) and our ability to predict the long-term consequences of silvicultural practices (the management model). We illustrate this with a diagram containing two feedback loops (fig. 3).

The left-hand loop through the conceptual model and process studies is the primary way to improve the conceptual model. The loop begins when available knowledge is synthesized into an initial

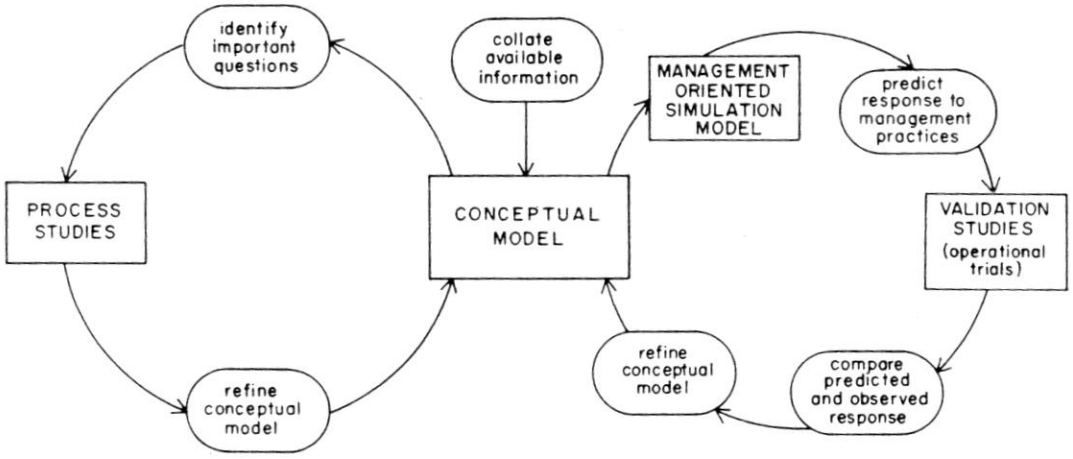

Figure 3.--Feedback loops between research and management operations.

conceptual model describing ecosystem structure and function. The conceptual model helps determine the priorities for process studies. In turn, the results of the process studies serve to refine the conceptual model.

The right-hand loop through the conceptual model, the management model, and the operational trials (fig. 3) enables us to make increasingly reliable predictions for forest management. Once constructed, the management-oriented simulation model can be updated to incorporate refinements in the conceptual model that have resulted from process studies. Furthermore, validation of the management model will improve both it and the conceptual model. Note that discrepancy between predicted and observed responses forces modification of both models; agreement reinforces confidence and discourages change. Neither discrepancy nor agreement is necessarily good or bad. Discrepancy opens up exciting possibilities for research; agreement means that land managers have a useful tool on which to base their decisions.

With diligent and creative effort by researchers and land managers, steady progress is inevitable. But the rate of progress cannot be measured without a clear goal. There is no reason to refine the management model unless it is inadequate for predicting responses within prescribed limits. Selection of such responses and limits is the responsibility of researchers and land managers together.

Efficient progress toward an understanding of the long-term effects of silvicultural practices requires cooperation among forest managers and many research disciplines: silviculture, geology, soils, nutrition, mensuration, microbiology, plant physiology, entomology, pathology, economics, and perhaps others. Information must flow freely across disciplines, as well as between researchers and land managers. Some validation studies must be long-term, perhaps as long as two or three rotations. These require thorough documentation and conscientious protection of study sites. In addition, existing studies and data sets should be used by many researchers if the studies are to realize their full potential. Cooperative studies are essential for all these reasons.

Existing cooperative research projects can help with the coordination of new studies. Such projects include the Regional Forest Nutrition Research Project (Peterson and Gessel 1983), the CRAFTS (Coordinated Research on Alternative Forestry Treatments and Systems for Forest Vegetation Management) program (Walstad et al. 1982) and the North Carolina State Forest Fertilization Cooperative in the southeastern United States (Allen and Duzan 1983), as well as the entire IUFRO program. With modest funding, such cooperatives can help (1) coordinate research to avoid duplication, (2) coordinate large-scale testing of models already under development, and (3) provide forums where researchers and land managers can discuss results and needs. Assignment of research priorities and standardization of methods are other possibilities, but we must keep in mind that the objective is to promote progress, not stifle creative thinking. In general, our goal is to use data efficiently to solve land-management problems. If we can assure that this will happen, we have a logical basis for seeking expanded funding for research into the long-term behavior of forest ecosystems.

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