United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

General Technical
Report
PNW-GTR-539
June 2002

Understanding the Compatibility of Multiple Uses on Forest Land: A Survey of Multiresource Research with Application to the Pacific Northwest

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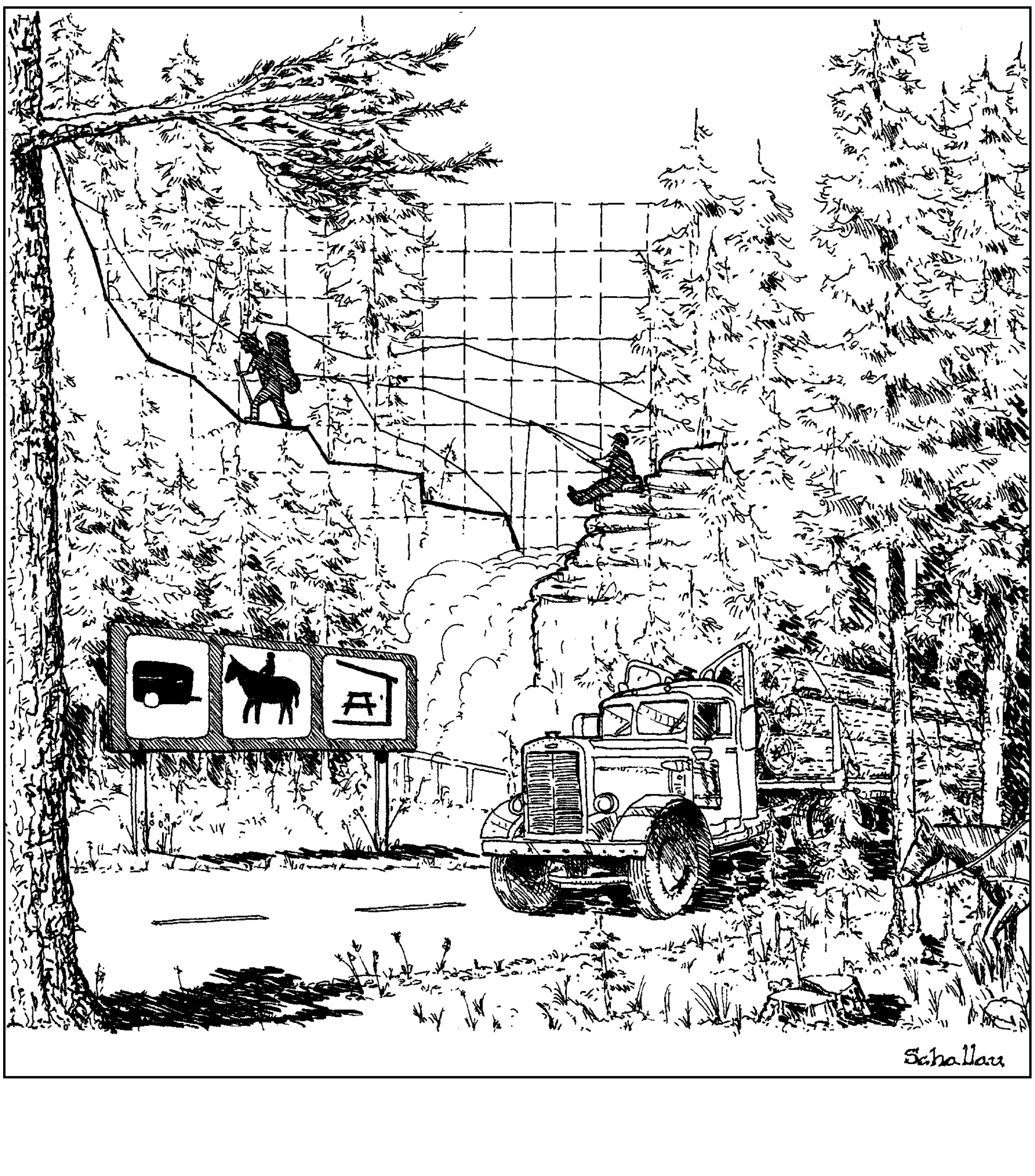

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Abstract

Stevens, James A.; Montgomery, Claire A. 2002. Understanding the compatibility of multiple uses on forest land: a survey of multiresource research with application to the Pacific Northwest. Gen. Tech. Rep. PNW-GTR-539. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 44 p.

In this report, multiresource research is described as it has coevolved with forest policy objectives—from managing for single or dominant uses, to managing for compatible multiple forest uses, to sustaining ecosystem health on the forest. The evolution of analytical methods for multiresource research is traced from impact analysis to multiresource modeling, and examples of true joint production of forest products, goods, and services are given. Empirical results from studies related to wood compatibility in the Pacific Northwest (PNW) are compiled. We found that:

- In most cases, joint production research has been too specific or too theoretical to be directly applicable by land managers. Meta-analysis may prove useful for generating general management guidelines.

- Compatibility studies generally demonstrate compatibility between wood production and other uses. This result depends on geographic scale of analysis.

- Increasing sophistication in modeling method and the dramatic increase in data describing interactions among forest uses will likely make future tradeoff analysis more realistic and useful. Current work in modeling timber-wildlife tradeoffs shows promise.

- Compatibility analysis can be useful for policy analysis by establishing standards of efficiency against which to evaluate policy alternatives.

Keywords: Multiple use, multiresource research, compatibility, joint production, production possibilities, tradeoff analysis, forest management, forest planning models.

Contents

Introduction

One hundred years of U.S. forestry research has shown that forests are complex, dynamic, and interrelated systems. The consumption or use of one forest product or service has an effect on other products and functions. The cost choice of designating an area as wilderness, for example, is the value of the foregone timber production. Similarly, clearcutting a mixed-age, mixed-species forest and replanting to a single-species forest reduces biodiversity. These land management choices are being made while increasing demand for traditional forest products has led to greater timber production from fewer acres. Research on tradeoffs and complementarity of production in the multiresource forest environment helps guide these choices. The research challenge is to determine if, and at what level, timber harvest and other forest services and products can complement one another. The management challenge is to follow these science-based guidelines and to manage appropriately.

Dana (1943) recognized that multiresource management is a challenge:

> Simultaneous use of the same piece of land for several purposes is often difficult since many uses compete with as well as supplement each other. Maximum production of timber interferes with maximum production of wildlife. Full utilization of forage reduces the yield of wood. Heavy cutting may make the forest less effective as a regulator of runoff and certainly impairs its value for recreation. Complete preservation of natural conditions for the benefit of the water supply or the nature lover puts a stop to all industrial use.

Timber harvesting is inextricably linked with other resources and can be compatible and beneficial for or detrimental to management of other resources. For example, harvesting mature aspen (*Populus* spp.) stands increases moose (*Odocoileus* spp. *Alces alces*) browse (DeByle 1985), whereas heavy streamside harvesting can have an adverse effect on stream temperature and salmon (*Oncorhynchus* spp.) survival (Beschta and others 1987).

Forest management goals are increasingly weighed against other forest values, and foresters are no longer given free rein to pursue their chosen management objectives. Writing in the mid-1970s, Nobel Laureate economist Paul Samuelson (1976) said that if the “ . . . pursuit of simple commercial advantage in forest management may have as a joint product reversible or irreversible effects upon the environment . . . ” then “ . . . the electorate will decide to interfere with laissez-faire in forest management.”

Public forest resource management has evolved from dominant use to multiple use, from a product output focus to an ecosystem health focus, from emphasis on one use or product for another to the joint production of multiple products and services. Behan (1990) asserts that “(m)ultiresource forest management . . . is rooted not in policy but in a fundamentally different perception of forest land. In viewing the forest as a single, interactive system of plants, animals, soil, water, topography, and climate, the argument over multiplicity is rendered moot. Simultaneous multiplicity is axiomatic—it is implicit in the concept of a system.”

As management objectives have changed, so have research focus and techniques. Much of multiresource analysis has used methods from economics and operations research. But given the multiresource nature of this research, most of the studies have drawn on the work of field scientists—biologists, hydrologists, ecologists, and others—as the basis for the analysis. Many, particularly the earliest, studies are based almost exclusively on field studies, often taking measurements of a second resource after one or more levels of intensity of timber harvest.

The integrated nature of this research has brought together scientists from different disciplines and traditions. There have been many roadblocks, however, to true multiresource research. What Behan (1997) calls "separatism" has long been an obstacle. Different world views as well as analytic techniques have made it difficult for scientists from different areas of expertise to communicate across disciplinary boundaries. Institutional boundaries also have impeded cooperation within public agencies.

Many different frameworks can be used for describing and synthesizing multi-resource research. This paper reviews the research related to multiresource management and joint production of timber and other forest resources from several analytical perspectives. Multiresource research in forestry has two components: valuation and production possibilities. Valuation refers to public preferences and social values and tries to provide guidance on the desirability of increasing one forest use even if that means decreasing another. Production possibilities refers to the productive capacity of the land and the compatibility of one forest use with another. Compatibility research tries to provide guidance on the cost of increasing one forest use at the expense of other forest uses. This paper emphasizes compatibility research including that undertaken as part of the wood compatibility initiative.[1]

The paper is organized as follows. In the history section, we present an introduction to the changing policy environment and corresponding multiresource research. In the modeling section, we present a conceptual framework for understanding multi-resource research with an emphasis on compatibility research. The empirical results of the previous research summarizes what we know about wood compatibility with other resources. In the following section, we emphasize research done in the Pacific Northwest. We conclude with a discussion of evolving directions of integrated multi-resource research.

A Brief History of Multiresource Policy and Research Trends

Changes in resource management have been driven by more than just increased knowledge about multiple resources. Management strategies are based on both science and policy. Public opinion, government policy, and market forces all have contributed to new directions in management. Science has always been a contributor but not necessarily the primary driver in multiresource management. Therefore, a discussion of the evolution of the forces that shaped multiple-use policies is necessary background to the research that supported or evolved from these policies.

Forest Reserves

Forest management in the United States was born as a reaction to the perceived lack of stewardship applied to American forests at the end of the 19th century. The objectives of Gifford Pinchot, the first chief of what was to become the USDA Forest Service, were ". . . to provide a series of examples of improved treatment" to prevent destruction of the forest associated with timber harvest "under the usual methods of lumbering" (quoted in Wilkinson and Anderson 1985: 19). It is not coincidental that the

[1] The USDA Forest Service, Pacific Northwest Research Station has funded a 5-year initiative to better understand the compatibility between wood production and other forest values in the Douglas-fir region and southeast Alaska. This report is funded through that initiative.

establishment of scientific forestry in the first decade of this century coincides with the highest annual harvest levels experienced up to that time in this country—26.4 million m^3 in 1906 and 1907 (Davis 1966).

The USDA Forest Service was established in this environment. The Organic Act of 1897 recognized both timber production and watershed protection as objectives of the "forest reserves," as the national forests were originally called (Wilkinson and Anderson 1985). It authorized active management and was viewed as a compromise between advocates of preservation and those for private exploitation (Bowes and Krutilla 1985). The Forest Service established its first experiment station in 1908 in Arizona. An important research area topic for this station was the relation between forest cover and watershed conditions particularly as it related to runoff and infiltration (Fedkiw 1999).

During the first half of the 20th century, local land users were the driving force behind the management of national forest resources. The principal constraint on resource uses and management was that they be applied in ways that would protect the permanence of both the flow of national forest uses, products, and services and the resources themselves (Fedkiw 1999).

Early federal research focused on trees, soil, and water. States had (and still have) the primary role of managing wildlife and fish populations and regulating hunting, fishing, and trapping. Whereas early wildlife management efforts focused on controlling livestock and wildlife predators, the role of the national forest was limited to habitat management. The Depression-era Civilian Conservation Corps invested much effort into improving habitat on public lands.

Before World War II, the national forests were seen as a "reserve" to be used when needed to meet national timber demands and to supplement private supply (Wilkinson and Anderson 1985). Industry was particularly interested in a limited cut from national forests to prevent flooding the market.

Post-World War II Economic Expansion

After the war, that role changed. It was a time of economic expansion and increasing household wealth—leading to increased pressure on the national forests for both commodity production and recreation and leisure activities. The Nation adopted policies aimed at making home ownership affordable for most households, effectively increasing housing demand. Consequently, from 1945 to 1970, national forest timber harvest rose an average of more than 5 percent per year. Figure 1 traces Pacific Northwest stumpage prices (in constant 1982 dollars) from 1909 to 1998. Stumpage prices showed only a modest upward trend until 1947. The economic expansion of the 1950s through mid-1960s sent stumpage prices higher in spite of increased public timber harvest. Beginning in the mid-1970s, stumpage price volatility has been the norm.

After timber harvest, mining and grazing have had the largest impacts on public lands. In the 1950s and 1960s, mining claims were viewed as having negative impacts on other resources (including timber), often through spurious claims on public lands that used a disproportionate amount of public resources (both physical and human) (Fedkiw 1999: 39-42). Overgrazing on public land brought about a stronger emphasis on balancing livestock use with grassland and timber management.

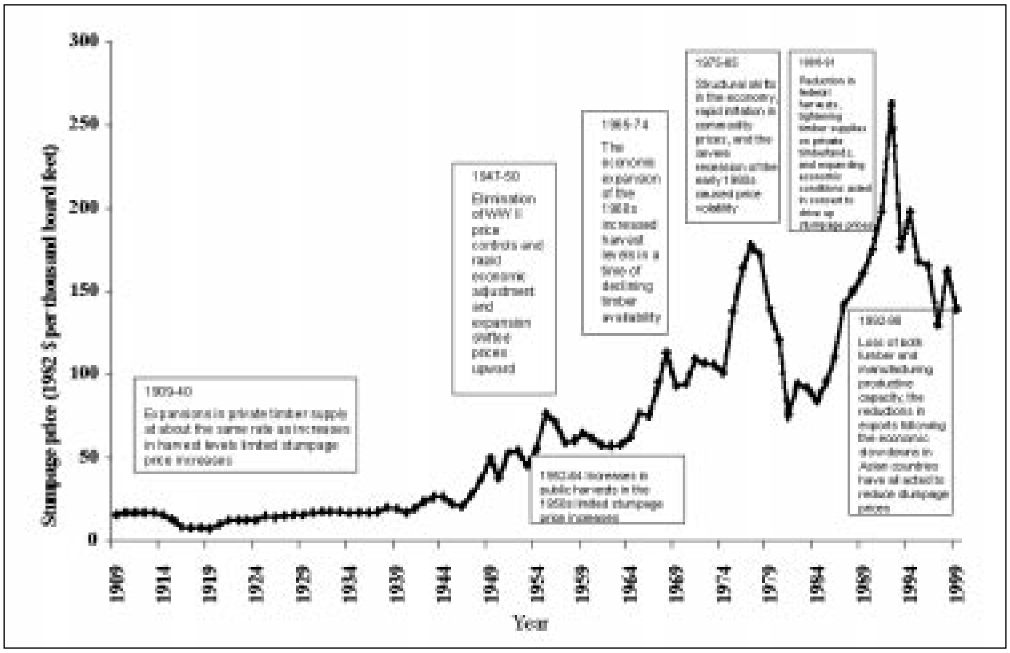

Figure 1—Pacific Northwest stumpage prices, 1909-98.

Although much early wildlife management research concentrated on game species, by the 1950s, there was growing attention to certain nongame species, particularly rare or endangered species. Examples include habitat management for Kirtland's warbler (*Dendroica kirtlandii*) in northern Michigan, a California condor (*Gymnogyps californianus*) in California, and osprey (*Pandion haliaetus*) in Oregon, all begun in the 1960s.

It was at this time that multiresource research first appeared in the forest economics literature with Gregory's (1955) model of joint production of timber and forage. This marked the beginning of quantitative modeling of the timber and other resource allocation problem.

Multiple Use Vs. Dominant Use

The Multiple-Use and Sustained Yield Act (MUSY) of 1960 defined multiple-use management as the judicious use of land so as to best meet the needs of the American people (Bowes and Krutilla 1989: 32). It required joint consideration of the major outputs from the national forests (Krutilla 1987). Alston (1976) viewed the act "as an attempt to put others on an equal footing with the industrial users of the forests." The MUSY Act mandated that national forests be managed for multiple uses and sustained yield of their products and services, that the various renewable surface resources be used in combinations that best meet the needs of the American people, that the relative values of the various resources be considered, and that decisions not be limited to use combinations that gave the greatest dollar return or greatest unit output (Fedkiw 1999). The act established legislatively, for the first time, that wildlife and fish habitat management were valid purposes for designating and administering national forests.

Land use planning under the MUSY Act involved coordinating potentially conflicting uses rather than zoning for single uses, but in practice often led to dominant uses. It became an increasing source of conflict when clearly conflicting uses were considered. The incompatibility of certain uses such as timber harvest and wilderness led to the National Wilderness Preservation Act of 1964. The act designated existing wilderness (3.7 million ha) as the National Wilderness Preservation System and directed that the remaining 2.2 million ha of primitive areas be reviewed for possible wilderness designation.

Although multiple-use planning was mandated under the MUSY Act, resource managers were predominantly trained in resource-specific disciplines. Often the management result was viewed as adjacent, single-resource, land use allocations (Cawley and Freemuth 1997). There was much skepticism about multiple-use policy because, in the past, multiple use came to mean dominant use (Bowes and Krutilla 1989), and the feeling prevailed that forest management had often followed a zoning model of many dominant uses.[2] The result was what Behan (1990) called "multiple use by adjacency." In 1970, the Public Land Law Review Commission advocated that a "dominant-use" policy be adopted for the U.S. public lands, but the policy change was never approved (Vincent and Binkley 1993).

Timber use production was the most prominent of the dominant uses. The Forest Service 1970 Timber Review (USDA FS 1973) emphasized increasing and extending timber supply to meet expected increased demand through intensified forest management, as well as better utilization and increased recycling. That document devoted just one page to environmental factors related to intensification of forest management. A supplementary report (West 1972), however, detailed in 87 pages the impacts of intensive management on nontimber resources on the national forests of the Northwest. One contributor to the dominant-use outcome on Forest Service lands was funding allocation. During the 1960s, timber sale administration on national forests was funded at 96 percent of the planned level, whereas reforestation and stand improvement were only funded at 39 percent (Cliff 1973).

Research has given some credence to single output production. For instance, Gregory (1955) showed under which iso-cost patterns single output production would be justified. More recently, Vincent and Binkley (1993) have shown under what conditions single output production may be most efficient. We note that in this debate, scale is a confounding factor; what may be multiple use at the forest level, may actually be dominant use at the stand level with some stands allocated to old-growth dependent species habitat, others to wilderness, and still others to commercial timber production.

Environmental Legislation

Concurrently with the debate surrounding how to account adequately for nontimber values of forest land, legislation was passed that took some of the management discretion away from land managers. The National Environmental Policy Act (NEPA) of 1969 formalized a requirement for accountability in the public forest land allocation decision (Bowes and Krutilla 1989: 34). The NEPA made environmental considerations equal to economic considerations and technical forest management. The Endangered Species Act (ESA) of 1973 gave absolute precedence to the

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[2] A point of view exemplified in a 1944 article by Pearson that concluded that "(w)hen foresters have developed an effective program of specialized use, they will realize that wild-land management is nothing more than a form of agriculture."

management of habitat to maintain and restore the viability of listed endangered wildlife, fish, and plant populations and indirectly called for action to protect sensitive and threatened species from becoming extinct. The ESA explicitly banned economic considerations in the listing decision.

Much of the research during this period related to the impacts of timber harvesting on other resources (e.g., game species, water quality, and recreation, etc.). Stone's 1973 report on logging effects on soil and water listed 28 research papers on water-related issues and 17 on soils from the late 1960s and early 1970s. Webb's (1973) companion paper on fish and wildlife listed five research studies on logging and wildlife impacts and nine on logging and fish relations. Because of the ESA, some research emphasis focused on measurements of biodiversity and nongame "indicator" species and fish. Research also began moving from descriptive studies to what Chapelle (1966) called "diagnostic" studies with more emphasis on mathematical modeling. For example, the timber harvest scheduling issues study in the mid-1970s (USDA FS 1976) modeled the relative impact of various timber harvest scenarios on other resources.

The Forest and Rangeland Renewable Resources Planning Act and the National Forest Management Act

As more broad-ranging questions were being asked about forest conditions, it became clear that data were lacking for broad-scale assessment of forest resources. The Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA 1974) addressed the need for an assessment of forest inventories and the demands for forest land services. The RPA also called for inclusion of cost dimensions. The legislation required that national program planning be linked directly with on-the-ground, multiple-use planning at the forest and ranger district levels (Fedkiw 1999).

The National Forest Management Act of 1976 (NFMA 1976) required an economic evaluation of explicitly documented alternative management strategies for each land area, with a balanced consideration of the potential mix of all goods and services from these lands. The act reaffirmed the policy objectives of the MUSY Act and explicitly added wilderness to the multiple-use purposes of national forests (Fedkiw 1999).

Because of the lack of data on harvesting effects on other resources, conservative approaches were adopted to account for them. The Forest Service partially justified its use of biologically maximum sustained yield (as opposed to the shorter economic rotation) on the basis that it yielded higher values of other goods such as water, recreation and wildlife, than the economic timber rotation (Newman 1988).

In lieu of being able to accurately value many of these nonmarket forest goods and services, administrative systems attempted to account for them in other indirect ways. In the late 1970s, the Forest Service classified a significant (>10 percent of total) acreage of commercial forest land as "special." On these lands, the Forest Service incurred higher costs, or accepted lower timber production, or both, in order to increase nontimber outputs over what would result from management in a "standard" land classification (Fight and Randall 1980). The NFMA stipulated that stands shall have reached maximum mean annual increment before harvest, but that exceptions may be made ". . . after consideration has been given to the multiple uses of forest including, but not limited to, recreation, wildlife habitat, and range . . . " (Calish and others 1978).

The multiresource nature of forest management was recognized in the NFMA as it required that each national forest use an interdisciplinary team to develop its forest plan. Better interdisciplinary communication and understanding within the national forests developed slowly as the background of Forest Service personnel changed from predominantly foresters to a mix of specialists in wildlife, recreation, hydrology, landscape architecture, and other fields. A major management paradigm shift took place with the publication of "Wildlife Habitats in Managed Forests: the Blue Mountains of Oregon and Washington" (Thomas 1979). The prevailing philosophy that "good timber management is also good wildlife management" had been modified to "good timber management can be good wildlife management if it is done correctly" (Fedkiw 1999: 176), especially through good communications among specialists and a good understanding of habitat needs.

During this time, regional goal setting became more institutionalized. Montgomery and others (1999) describe public land management policy as a "command and control" approach where the Forest Service sets regional production targets for timber, range, and other uses under the RPA and evaluates the performance of regional administrators based on their ability to meet these targets. This required the development of forest-level planning tools, particularly mathematical programming models, that allowed analysts to tackle previously intractable large-scale resource allocation problems (Johnson and Scheurman 1977) to assist in setting targets that were cost-effective and attainable. The NFMA established the linear programming model FORPLAN to be used by the national forests to develop their multiple-use plans (Iverson and Alston 1986).

By the late 1970s, it was becoming apparent that satisfying the many nontimber demands on forest resources would involve tradeoffs, including reduced wood production (Fight and others 1979). Consequently, much of the research in the early 1980s took the form of evaluating tradeoffs between resource uses (e.g., costs in terms of reduced timber harvest of having better water quality). Examples include Fight and Randall (1980), tradeoffs between visual quality and timber harvesting; Connaughton and Fight (1984), applying tradeoffs to forest planning; Huppert and others (1985) and Meehan (1985), timber management implications for fish habitat; Wood and others (1985), compatibility of even-age management and red-cockaded woodpecker (*Dryocopus pileatus)*; and Bowes and others (1984), timber harvest and water yield, just to name a few.

Concurrently, an increase in computing power and the development of more powerful software by the mid-1980s facilitated more sophisticated, larger scale analysis. Increasingly complex mathematical programming models were developed to deal with previously intractable multiresource questions. Examples include multiresource modeling by Hof (1983) and Joyce and others (1983, 1986, 1990) and regional multiresource models like the southeast Alaska model (Fight and others 1990).

Ecosystem Management and Sustainability

Ecosystem management has been the guiding management principle for the Forest Service since the mid-1990s. Ecosystem management has been described as an evolutionary extension of multiple use, guiding its application through greater scientific understanding (Gorte 1999) reflecting the advances in research over the previous 20 years.

Ecosystem management research has often meant harvesting timber only in support of other resources. For instance, Northwest Forest Plan (NWFP) research emphasizes ecosystem management and management in riparian zones and late-successional reserves as well as the effects on other resources of different silvicultural and logging practices (Haynes and Perez 2000). Other ecosystem management research has undertaken large-scale manipulation of forests to measure impacts (Monserud and Peterson 1999) usually under highly constrained harvesting conditions.

If ecosystem management brought more holistic thinking to forest management, then, in the late 1990s, sustainability added a more explicit temporal element. Making forest resources sustainable, in the sense of passing on healthy resources to succeeding generations, was the driving force for forest management throughout the 20th century. At the beginning of the 21st century, the question of how to measure sustainability is being considered in a more quantifiable way. In fact, the term itself was so contentious that “resiliency” rather than “sustainability” was used in the interior Columbia basin project because of the lack of agreement about definitions (Haynes 2000). Although the Montreal Process[3] set the direction for sustainable forest management, scientists are struggling with metrics for determining success.

Bormann and others (1994) defined three steps for calculating sustainability:

- Select candidate goods, services, and forest conditions desired by society.

- Determine ecosystem patterns and processes thought to be needed for the desired goods, services, and forest conditions.

- Jointly evaluate and set priorities among societal demands and ecosystem patterns and processes.

There has been an evolution of goals from the sustainability of individual product outputs to the sustainability of whole ecosystems. As a result, there is the recognition that sustainable timber harvest levels do not guarantee sustainable levels of other goods and services. The sustained yield concepts of the MUSY Act from the early 1960s have proven to be inadequate when applied in the multiresource environment. The criteria and indicators approach of the Montreal Process is another step in assuring that the full array of forest values, goods, and services are considered in land management decisionmaking. The discussion of joint production and sustainability are inseparable because the production of one output will have repercussions on other outputs and services.

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[3] The Montreal Process was an initiative of the government of Canada that involved meetings in 1993-95 and produced a comprehensive set of criteria and indicators for forest conservation and sustainable management.

The Theory of Joint Production and Production Tradeoffs

Social welfare theory provides a general normative model for an economy to allocate resources to the uses that maximize social well-being. This model provides a context for understanding multiresource research and making the commonalities explicit. We also use it here to guide the subsequent discussion of existing compatibility research. The components Bormann used to evaluate sustainability are also components of forest-level planning and regional target setting and are clearly identified in the social welfare model. They are:

- The definition of outputs.
- The specification of production relations.
- The assessment of social values for the outputs relative to one another.

The version of the social welfare model that follows was adapted from Tresch (1981: 27-29):

$$
\begin{aligned}
\max \quad & W = W(U^h(y_i^h, x_j^h)) \\
s.t. \quad & F(Y_i, X_{ij}) = 0 \\
& \sum_h y_i^h \leq Y_i \quad \forall i \\
& \sum_h x_j^h \geq \sum_i X_{ij} = X_j \quad \forall j
\end{aligned}
$$

h = 1,...,H individuals
i = 1,...,I goods and services
j = 1,...,J inputs to production,

where W represents social well-being as a positive function of the well-being, or utility, U^h, of each individual, h, in society. Individual utility depends on individual consumption of goods and services, y_i^h, and individual supply of inputs to production, x_j^h, including labor, investment in capital, and basic resources such as land, forest, and water. Total production of goods and services, Y_i, is limited by the total availability of inputs, X_j, and is governed by the joint production function $F(Y_i,X_{ij})$, which describes the production relation between inputs and outputs and the allocation of inputs j to the production of outputs i, X_{ij}. The summations are simply for accounting; the first constrains consumption of a good not to exceed production of that good, and the second constrains the use of an input not to exceed supply of that input.

The basic model can be used to describe the allocation of resources over time (sustainability) by making time explicit so that U is intertemporal utility, future generations count in social well-being, and capital stocks, resource stocks, and investment appear in the production function. The resource allocation that solves this problem and maximizes social well-being is called socially efficient. Three key results arise from this model. For social efficiency:

1. The relative value of any two goods, i and i' to an individual consumer (known as the marginal rate of substitution, MRS) must be the same across all consumers, h and h':

$$
MRS^h_{i \text{ for } i'} = \frac{\partial U^h / \partial y_i^h}{\partial U^h / \partial y_{i'}^h} = \frac{\partial U^{h'} / \partial y_i^{h'}}{\partial U^{h'} / \partial y_{i'}^h} = MRS^{h'}_{i \text{ for } i'} .
$$

2. The ratio of the marginal products of any two inputs, *j* and *j'*, in the production of any good (known as the marginal rate of technical substitution, MRTS) must be the same across all goods, *i* and *i'*:

$$MRTS^{i}_{j\ for\ j'} = \frac{\partial F/\partial X_{ij}}{\partial F/\partial X_{ij'}} = \frac{\partial F/\partial X_{i'j}}{\partial F/\partial X_{i'j'}} = MRTS^{i'}_{j\ for\ j'}.$$

3. The relative value of any two goods, i and i', to an individual consumer (MRS) must be equal to the production tradeoff between the two goods (known as the marginal rate of transformation, MRT):

$$MRS^{h}_{i\ for\ i'} = \frac{\partial U^h/\partial y^h_i}{\partial U^h/\partial y^h_{i'}} = \frac{\partial F/\partial Y_i}{\partial F/\partial Y_{i'}} = MRT_{i\ for\ i'}.$$

In a pure market economy, consumers and producers act independently, buying and selling goods and factors of production. Relative prices, *Pi/Pi'*, are set in markets so that the optimality conditions above are met automatically as long as all goods and inputs are purely private and suitable for market exchange. For example, in a market economy, the third optimality condition becomes:

$$MRS^{h}_{i\ for\ i'} = \frac{P_i}{P_{i'}} = MRT^{h}_{i\ for\ i'}.$$

But markets fail to meet the optimality conditions in the case of resources, like forest land, that contribute to the production of goods that have a large public goods component and, hence, are not suitable for market exchange.

In the United States, markets play a large role in allocational decisions. But we also try to improve over the pure market allocation by making use of various forest policy interventions including regulation on private forest land, price adjustments via taxes and subsidies, and public ownership and management of forest land for nonmarket goods and services. This requires knowledge of all the relations represented in the optimality conditions: relative valuation of goods by individuals, marginal products of all factors in the production of all goods, and production tradeoffs between any two goods. Better or more complete knowledge leads to more successful forest policy.
In the 1970s and 1980s, for example, the USDA Forest Service used large-scale mathematical programming models to set regional goals for the national forests that came as close to meeting the third optimality condition as current knowledge allowed. It was a cumbersome and highly imperfect process that highlighted the inadequacy of current knowledge to support such a task; but it helped identify areas where small increments in knowledge might generate large benefits in improved policy.

For the purpose of this paper, the most important of the optimality conditions is the third one, which defines the relation between valuation of multiple forest uses relative to one another (*MRS*) and the compatibility of those uses on a limited forest resource base (*MRT*). In particular, compatibility research highlights production tradeoffs as represented by the marginal rate of transformation of one into the other, *MRT*. That is defined by the joint production function, $F(Y_i, X_{ij})$, which defines the set of all possible combinations of goods and services that can be produced for a given set of inputs and production technologies (the production possibilities set). For forest land, goods and services (hereafter referred to as forest uses) include commodities (such as timber, mushrooms, and ornamental foliage), interactive uses (such as recreation and visual aesthetics), and ecosystem services (such as carbon storage, water flow, and biological diversity). Inputs include abiotic resources (such as water, soil, and nutrients), biotic resources (such as existing trees, shrubs, grasses, wildlife, and microbes), and management effort. Production activities include active management (such as silvicultural activities, road building, recreational development, active wildlife management, and fire control) and passive management (such as reserves and wilderness), both in the context of ongoing ecological processes and disturbances (such as vegetation growth and succession, fire, disease, and wildlife population dynamics). Bowes and Krutilla (1989) observe that:

> In practice, we might never explicitly be presented with the overall production function. . . . For example, one researcher might investigate different spatial patterns of timber harvesting, identifying their effects on the production of timber and water flow. Another might consider the effect of timber management practices on the volume of herbage available for livestock or wildlife. Studies such as these provide us with partial production relations, or at best a few elements of the production possibilities set. A production function should be thought of as a convenient way to describe the most effective combinations of all such management practices, whether for the forest as a whole or for particular units of the forest.

In the following general discussion of production possibilities sets, tradeoffs between two forest uses are depicted; they are partial relations. The two uses, *T* and *R*, can be anything (e.g., timber and wildlife, elk and cattle, water quantity and water quality, and so on). But in fact, the production possibilities set has as many dimensions as the set of forest uses being modeled. Forest uses that are not explicitly modeled are assumed fixed at some level. At least one input is fixed and hence limits production (usually the land base and some attributes of it). If no input were fixed, there would be no production tradeoffs.

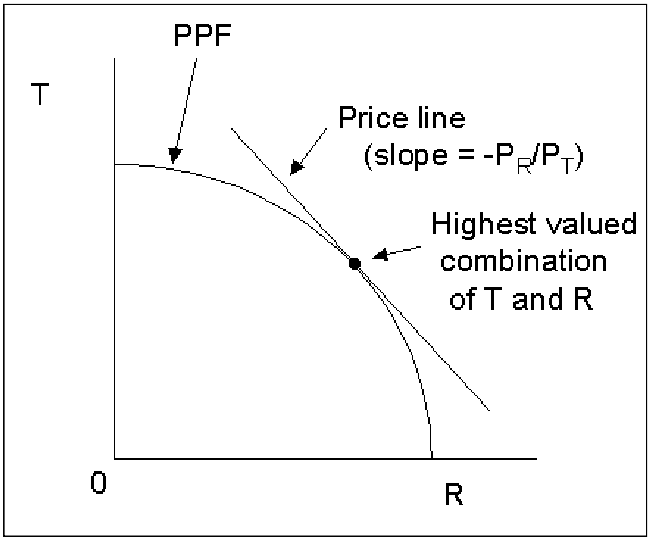

Figure 2—Production possibility frontier (PPF) showing two competing, but compatible, forest uses.

Figure 2 depicts the most common type of production possibilities set for two uses. The outer bound of the production possibilities set is known as the production possibility frontier (PPF). Combinations of forest uses *T* and *R* that are inside the PPF are inefficient because one use could be increased without reducing the other, resulting in an unambiguous gain. But along the PPF, any increase in one use results in a decrease in the other use, hence there are the tradeoffs that are identified in the third optimality condition. The slope of the PPF is the MRT for the two uses and it describes how much one use must be reduced in order to increase the other. The desirability of moving along the PPF from one combination of uses to another depends on the relative value of the two uses (*MRS*). The highest valued combination of uses is at the tangency of the PPF and a price line representing the relative values of the two outputs to society. For market goods, relative prices can be observed. But most of the cases that concern forest policymakers involve public goods that are not marketable and, hence, relative values are unknown.

Research into the compatibility of wood and nonwood uses of forest land attempts to improve knowledge of production tradeoffs (*MRT*) in order to increase the effectiveness of forest policy interventions. The other half of the equation, relative valuation or *MRS* of forest uses, is also important and is the domain of valuation research.

Knowledge of the nature of production tradeoffs can help answer the following questions:

1. Is current management inefficient? Again, if current management falls inside the PPF, there is an opportunity to increase one use at no cost in terms of foregone other uses. Forest policymakers should be interested in knowing where such inefficiencies occur because inefficient resource management is wasteful.

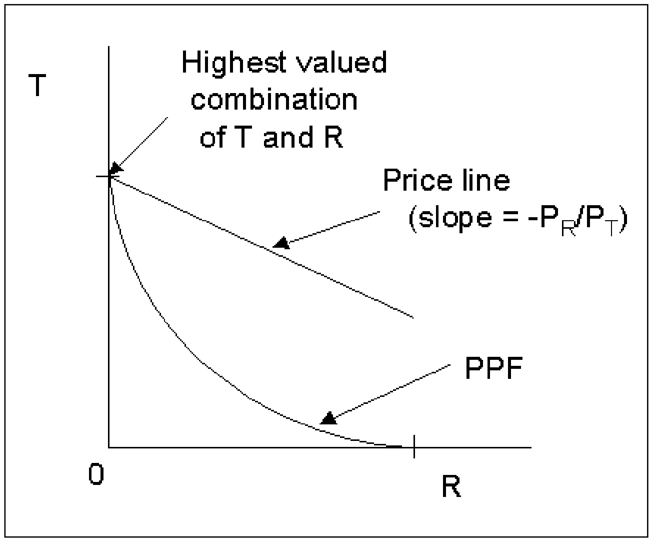

Figure 3—Production possibility frontier (PPF) showing two rival forest uses.

2. What are the tradeoffs along the PPF? Is it optimal to manage for a combination of outputs (multiple use) or for one particular output (dominant use)? The curvature of the PPF reflects the degree of compatibility of the two forest uses. In figure 2, which depicts compatible but competing uses, increasing *T* from zero requires only small reductions in *R* initially, but as *T* is increased further the corresponding reduction in *R* becomes bigger and bigger. For the concave (to the origin) PPF depicted in figure 2, multiple use is always superior unless the price line is either so steep or so flat that the optimal point is at the corner.

Figure 3 depicts a different type of production possibility set, referred to by Duerr (1960) as "rival products." Increasing *T* from zero requires a large reduction in *R*, and vice versa. In this case, it is optimal to manage for one use or the other (dominant use). Again, relative values determine which use is preferred. In figure 3, the value of *T* is sufficiently high relative to the value of *R*, that this site should be managed for *T* only.

There is one other type of production possibility relation worth noting—complementary goods. For some forest uses, an increase in one leads to an increase in the other, at least over some range. Timber harvest and water yield is one example. Complementary goods can be modeled as fixed bundles—increasing one increases the other as a "by-product." But there may be tradeoffs between the bundle and other goods. For example, Ffolliott and Thorud (1977) found that thinning in northern Arizona ponderosa pine forests increased water yield, but that water quality deteriorated.

3. If current management is inefficient, why is that so? Is it due to inadequate knowledge—would better planning, modeling, and decisionmaking suggest better management alternatives? Or is it institutional? For instance, private landowners may not produce enough goods that are not marketable, such as biodiversity conservation, because there is no incentive to produce more. Likewise, government agencies

face many political factors that limit management options on public land. If policy-makers understand the nature and the reason for inefficient resource management, they will be more likely to identify effective forest policy interventions.

Production tradeoffs occur (the production set is finite) because at least one input is limiting—there is a fixed amount of the input to be allocated between uses. For forest uses, the primary fixed input is the land in its current condition. This raises the issue of geographic scale. The degree of compatibility of forest uses that an analysis reveals may well depend on the scale of the analysis. Two uses may not appear to be compatible at the stand level but may be compatible at the forest level. For example, territorial wildlife species with large territory requirements and a strong preference for old-forest conditions, such as the northern spotted owl (*Strix occidentalis caurina*), may appear to be incompatible with timber production at the scale of a single watershed, but may be compatible with timber production at the regional scale.

A Survey of Multiresource Research

One of the earliest references to multiresource research comes from the forest economics literature. Gregory (1955) used the joint production model from microeconomic theory to formulate the stand-level multiple-use problem using timber and forage as examples. He described a set of iso-cost curves. These are essentially PPFs for the case of a limited budget. For each budget level, the optimal combination is that at which the ratio of relative values (the slope of the “iso-revenue line”) is equal to the ratio of the marginal costs (the slope of the iso-cost curve) satisfying the third optimality condition (*MRS* or relative value equals *MRT,* which is equivalent to the ratio of marginal costs). From these points, an expansion path can be constructed that identifies optimal combinations of the two forest uses for increasing levels of the budget constraint. Gregory’s expansion path example is interesting because it shows how the PPF can depend on the level of the fixed input (e.g., for land, varying the budget constraint is equivalent to varying the geographic scale of the analysis).

As noted earlier, this marked the beginning of quantitative modeling of the timber and other resource allocation problem. Hagenstein and Dowdle (1962) provided a conceptual model of the opportunity cost tradeoffs implicit in larger scale forest land allocation for uses (such as wilderness) incompatible with timber production. Muhlenberg (1964) estimated points on a PPF for pulpwood and deer. It is composed of a finite number of parts that approximate the continuous production surface of the theoretical model. Jones and Schuster (1985) applied this method to derive the expansion path of highest present value between elk (*Cervus elaphus*) carrying capacity and timber harvest.

There have been few studies that explicitly model the PPF for forest uses, but many multiresource studies model production tradeoffs in some way. In the following discussion, existing multiresource research is presented by visiting and revisiting the research with respect to a set of general modeling considerations: forest function or forest uses, modeling multiple resources, scale of analysis, optimization, and valuation.

Forest Function or Forest Use

Competing uses include wildlife, aquatics, biodiversity, carbon sequestration, special forest products such as mushrooms and decorative greenery, visual aesthetics, recreation, and timber. Determining measures of accomplishment for the forest uses can be difficult. For example, various approaches to measuring a trajectory of timber harvest over a period include using total volume harvested over the time horizon, annual sustainable yield, or present value of timber harvested over the time horizon. In another example, the recognition that forests are a diverse genetic pool with a necessarily wide array of biotic and abiotic components that should be maintained has raised the perplexing question of just how that diversity can and should be measured and monitored.

Wildlife—There are many descriptive studies that enumerate the habitat requirements that various wildlife species require. For example, Bull and others (1997) describe how 80 species of birds, mammals, reptiles, and amphibians use living trees, snags, and logs in the interior Columbia River basin for foraging, nesting, denning, roosting, and resting.

An example of habitat need and management prescription research was undertaken in 1970. A cooperative project between government agencies and the University of Montana determined certain ecological requirements of elk (*Cervus elaphus*) and the effects of logging, roads, and access on elk populations in the Little Belt Mountains in Montana. The research produced a series of recommendations for designing and conducting timber sales to minimize their adverse effect on elk (described by Fedkiw 1999: 178; Lyon 1979). Jones and Schuster (1985) used the results to model timber production and elk habitat (specifically, summer range effectiveness).

The integrated approach pioneered by Thomas (1979) in the Blue Mountains had a large impact on integrating the science of wildlife habitat needs with practical management guidelines. Species habitat needs assessments were wedded to consistent management guidelines for timber harvesting and other interventions. An example from the Southeastern United States showed that red-cockaded woodpecker and clearcutting were compatible under certain restrictions on adjacent lands (Wood and others 1985).

Many economic studies of habitat management exist in the forestry literature. Hyde (1989) analyzed the cost of providing red-cockaded woodpecker habitat. Montgomery (1995) specifically analyzed the cost of the “well-distributed” wildlife habitat requirement of the NFMA for the northern spotted owl. Economic considerations were also the focus of a study on the effects of forest management on anadromous fish habitat (Meehan 1985).

Two studies looked at tradeoffs between timber and wildlife from the perspective of the PPF: Calkin (2001) used the northern flying squirrel (*Glaucomys sabrinus*), which prefers older coniferous forests, and Arthaud and Rose (1996) used ruffed grouse (*Bonasa umbellus*) and aspen in the Lake States.

Whereas most habitat-needs-based studies focus on species abundance, two recent studies compared the risk of extinction or likelihood of survival to the cost of timber reduction. Haight (1995) measured tradeoffs between the risk standard for population extinction and timber revenue. Montgomery and others (1994) estimated the marginal cost curve for owl survival likelihood.

Not all studies of this type evaluate the impact of intensive forest management. McComb (1993) simulated the impact of long rotations in the Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests of the Pacific Northwest on wildlife habitat.

Aquatics—Similar to findings related to wildlife habitat effects, studies have shown that timber harvesting and water quality and quantity can be complementary or conflicting depending on the goal. Two Western studies of timber management for improved water yields (snow management in the Rocky Mountains, Colorado [Bowes and others 1984] and California [Bowes and others 1992]) showed that management for joint products like timber and water may be justified "in a setting that would likely not justify management for timber alone." The same relation might exist for fire risk reduction in many small-diameter timber stands in the inland West.

There are many examples of silviculture-hydrology interaction across North America. Hornbeck and others (1997) summarized the hydrologic research at Hubbard Brook (Northeastern United States), which found that water yield increases that occurred after forest treatments resulted from reductions in transpiration and canopy interception. As cited earlier, Ffolliott and Thorud (1977) found that thinning in northern Arizona ponderosa pine forests increased water yield but that water quality deteriorated.

A prime example of translating scientific research for a management audience is the series "Influence of Forest and Rangeland Management on Anadromous Fish Habitat in Western North America" published by the Pacific Northwest Research Station in the early 1980s. A particularly good example from this collection is Chamberlin's (1982) paper on timber harvest effects on stream ecosystems in the West.

Biodiversity—Much of the research on biodiversity addresses the simplification of the landscape as forest land is altered through management for efficient timber production. Decreasing biodiversity increases the chances of species extirpation, so biodiversity and species viability are inextricably linked. Biodiversity issues have been particularly difficult for land managers, who have traditionally been site- or stand-oriented in their outlook, because viability of species depends on more than one site (Montgomery and others 1999). In one approach, Carey and others (1996) proposed a biodiversity pathway for forest management based on comparisons of biotic communities in old-growth, young natural, and managed forests. Lippke and others (1999) evaluated the opportunity cost of implementing the biodiversity pathways in western Washington and suggested incentive programs to induce landowners to choose these management regimes.

Common measures of species diversity fall into three main categories (Magurran 1988): species richness indices, species abundance or evenness models, and proportional abundance indices. Holland and others (1994) and Schulte and others (1999) use the third type, specifically Shannon's diversity index. Holland and others (1994) used multiple measures of vegetative diversity: stand species diversity, basal area diversity, and vertical crown diversity to compare economic tradeoffs with timber production. Schulte and others (1999) used the index for tree species diversity.

Hof and Raphael (1993) measured the relative abundance of wildlife diversity by maximizing (a) the expected species richness, (b) the minimum probability of viability among all species, and (c) the joint probability of viability across all species for 92 species of amphibians, reptiles, birds, and mammals sampled from five habitat types in northwestern California by using a static model. Bevers and others (1995) used the same 92 wildlife species and represented species viability using a logistic function in a dynamic model. Montgomery and others (1999) also used a logistic viability function to estimate economic tradeoffs between market-valued land uses and expected species richness for 147 bird species.

Carbon sequestration—Forests are often regarded as "sinks" for carbon as they keep carbon dioxide from building up in the atmosphere. High-quality wood also can help keep levels of atmospheric carbon low by serving as a substitute for construction materials such as steel, aluminum, brick, concrete, and plastic that require large amounts of fossil fuels during manufacture and transport and thereby increase the production of carbon dioxide (Oliver 1993). Van Kooten and Bulte (1999) considered a full range of values including carbon uptake to determine the optimal amount of old-growth timber that should be preserved on the British Columbia coast. Haener and Adamowicz (2000) also accounted for the contribution of carbon sequestration as an "environmental control service" to the nonmarket value of forests in Northern Alberta (along with biodiversity maintenance as a "passive use value").

Special forest products—There are various other nontimber or "special" forest products, some of which have well-established market values (Savage 1995, von Hagen and others 1996). There is scant research, however, on the joint production of special forest products and timber harvesting, although there is a long history of silvicultural research on the effects of density control. To the extent that special forest product production can be correlated with tree spacing and shading, production relations can be estimated. Davis (1999) suggested many management strategies for combining timber production and special forest products on multiple scales. Weigand (1998) described experimental prescriptions from high-elevation stands in the southern Oregon Cascade Range that emphasize alternative approaches for joint production of North American matsutake (*Tricholoma magnivelare* (Peck) Redhead) mushrooms and high-quality timber.

Visual aesthetics—Particularly in the West, visual perceptions strongly influence social acceptance of active management. Curtis and Carey (1996) characterized the recent phase of large clearcuts and short rotations as a "political and social disaster." Ribe (1999) tested perceptions of clearcuts versus 15-percent green tree retention and found little difference in the viewer's reaction, especially among those that were not informed of the ecosystem objectives of the green tree retention system. Two other studies have examined the costs of visual values production (Brown 1987) and the costs of scenic beauty (Fight and Randall 1980).

Timber—Before the emphasis on multiresource production, timber commanded the dominant share of research effort. This research centered around the maximum economic return to the forest landowner from timber harvest. The earliest models were simple, nonspatial, single-stand analyses. The earliest of these harvest scheduling models dates back to the mid-19th century: the Faustmann soil expectation value equation:

$$SEV_T = \frac{R_T - C_0(1+p)^T}{(1+p)^T - 1},$$

where SEV_T is soil expectation value derived from timber harvest in dollars per acre, T is the rotation period, R_T is the stumpage revenue received every T years, C_0 is the initial investment in site preparation and planting every T years, and p is the rate of interest. The best economic rotation is the age, T, that maximizes the soil expectation value.

Hartman (1976) adapted the Faustmann equation to include nontimber amenity benefits. The value of some amenity benefits, such as scenic value or habitat for wildlife adapted to old-growth forests, may rise with stand age. Other nontimber benefits, such as water yield, grazing, or habitat needs involving openings or young stands, might decrease in value with forest age (Swallow and Wear 1993). When these amenity values are not considered, the opportunity cost of timber harvest is foregone future timber harvest revenue. When amenity values are considered, the opportunity cost of timber harvest includes both foregone future timber harvest revenue and foregone amenity value of the standing timber. In that case, the optimal rotation may be longer or shorter than the Faustmann rotation, depending on whether the amenity value increases or decreases with stand age. If the rate of growth of amenity values is high enough, harvest may be foregone forever.

In an application of Hartman's model, Calish (1976) found for the Douglas-fir region and the nontimber values tested (deer, elk, water flow, trout (*Salvelinus* spp.), nongame wildlife, visual aesthetics, and mass soil movement) that the Faustmann formulation was quite robust; the optimal rotation changed only slightly. Many studies refined the Hartman model. Strang (1983) incorporated multiple-use characteristics in an optimal control extension of the Hartman formulation. Swallow and others (1990) accounted for the potential nonconvexity problems with the Hartman model by finding global optima. Snyder and Bhattacharyya (1990) formulated an alternative to the Hartman model in finding a global optimum solution. Riiters and others (1982) used a dynamic programming model and showed that joint production of timber and forage had a higher soil expectation value than either alone and that different outputs at different stages of the rotation can be most productive. Steincamp and Betters (1991) took the Riiters data and applied an optimal control model.

Modeling Multiple Resources

Models available for multiresource research include timber growth and yield models, wildlife population simulation models, water yield models, aesthetic impact models, and so on. Modeling capabilities have increased dramatically since Gregory (1955) first framed the multiresource problem. The evolution of multiresource models reflects two concurrent patterns: (a) increasingly sophisticated mathematical models and computers capable of running them and (b) increasingly complex interactions being modeled.

Early resource interaction models can be classified according to their scope. The type 1 model is a single resource static model with no spatial component. The input could be, for instance, the habitat needs of a particular species, and the output could be a measure of species viability. Type 2 models attempt to capture resource interactions over time, where the state of one resource is measured and then a management treatment is effected. The impact on the first resource is evaluated; this may be followed by subsequent treatments and evaluations. These models may or may not be spatially explicit.

Much of the research of the 1990s has evolved with the more holistic view of the interrelatedness of the forest system inherent in ecosystem management. The spatial aspects of forest interactions have been of particular interest, especially with regard to wildlife habitat needs. Eng and others (1991) used geographic information systems (GIS) and forestry and wildlife models for timber harvest-deer effects in British Columbia. The coastal landscape analysis and modeling study (CLAMS) model (McComb and others 2000) also used GIS to develop habitat relation models to evaluate how forest policies affect different measures of biological diversity.

These models all require predictions of the response of the resource to management activities. The predictive models differ dramatically in their sophistication and the quality of the information on which they are based.

Expert opinion—It is common to rely on expert opinion to estimate the impacts of management when empirical evidence provides insufficient data for modeling. For example, the Forest Ecosystem Management Assessment Team that evaluated alternative plans for public forest land in the Pacific Northwest relied on consensus of expert biologists to predict outcomes for several wildlife species.

Interdisciplinary teams, mandated for national forests by the NFMA of 1976, can be effective if a diversity of management impacts are examined and environmental variables are not easily quantified (Joyce and others 1983). In another example, two studies related to the timber harvest scheduling issues study (USDA 1976) by Sassaman (1976) and Randall (1976) used an expert opinion survey to obtain qualitative estimates of the effects of timber harvest on various nontimber resources.

The Northeastern United States decision model (Marquis and Stout 1992) is a hybrid of expert opinion and growth simulation models to support land managers charged with developing silvicultural prescriptions to achieve various timber, water, wildlife, aesthetic, and environmental goals. Montgomery and others (1999) used an expert opinion survey to establish habitat preference rankings for bird species in Monroe County, Pennsylvania. However, although expert opinion is often the only information available, the inherent subjectivity of this method makes peer review of the resulting analyses difficult.

Simulation models—The effect of management on a resource is usually the result of a complex system of individual relations and links. Mathematical models can be used to simulate these complex interactions in considerable detail, and they provide the flexibility necessary for policy analysis. As Behan (1990) notes:

> With a simulation model, managers can mimic the manipulation of one resource and see the anticipated response of all the other resources. And if they don't much care for the response, they can propose a different manipulation or perhaps none at all. Foresters in this scenario take a system view, which is the essence of multiresource forest management.

Spatially explicit wildlife population simulation models such as the Program to Assist the Tracking of Critical Habitat (PATCH), (Schumaker 1998) or the northern spotted owl model of McKelvey and others (1992) track wildlife populations for individual species on a particular landscape over time. Management activities can be imposed and the resulting effects on wildlife can be simulated. Liu and others (1994) developed a simulation model of wildlife population dynamics that attempts to bridge the gap between the landscape ecology focus on landscape structure and the economics focus on the economic effects of management options such as rotation lengths. The model, ECOLECON, predicts animal population dynamics, spatial distribution, and extinction probability, as well as future landscape structure and economic income from timber harvest.

However, even the most sophisticated mathematical simulation model must be parameterized. Often the parameters are themselves the result of expert opinion. For example, Nalle (2001) used a map of habitat scores for two wildlife species that were generated by experts to initialize PATCH simulations in a tradeoff analysis for wildlife and timber production.

Linked models—There is growing recognition that multidisciplinary research is essential to understanding complex ecosystem-level interactions. This has led to the linking of models from different disciplines. The Douglas-fir supply study (USDA FS 1969) was one of the first computer simulations that, in addition to forecasting regional timber supply under different scenarios, allowed the estimation of the effects of various harvest intensities (and road-building levels) on water yields, water quality, fish habitat, big game populations, and recreational use. Ohmann and Mayer (1987) were among the first to link inventory data with habitat models. Using similar methods, the western Washington timber supply study (WTSS) (Adams and others 1992) produced a set of harvest and timber inventory projections by ownership. An additional analysis linked the timber inventory projections of the WTSS with habitat suitability indices for 14 mammalian and 10 avian species based on their apparent preferences for various successional stages of forest vegetation. The change in relative habitat suitability for each species was determined based on the projected changes in needed vegetation types from the WTSS. Lippke and others (1999) integrated timber growth and yield models with habitat models in a mathematical programming framework to produce the biological and economic measures associated with different management strategies for western Washington. Hansen and others (1995) combined a forest model (ZELIG.PNW.2.0), statistical models of bird habitat relations, and an economic model (NEOTROP) to compute stumpage and products values. The environmental indicators model (Greenough and others 1999) used stand condition as an indicator of habitat.

Using a series of linked models including the Prognosis growth and yield model, it projected indicators of wildlife, water quality, visual quality, and timber values for spatial landscape analysis. The southeastern Alaska multiresource model (SAMM) drew from experts on timber, hydrology, fisheries, and wildlife (deer) to integrate the interactions resulting from forest management in the Tongass National Forest (Fight and others 1990). The resulting simulation model interlinked the four major process models.

Scale of Analysis

Studies range from stand-level management plans to large-scale regional models. The scale of the analysis has implications for the level of detail in the analysis, behavioral assumptions, limits on inputs, budget constraints, and the policy environment. Some analytical techniques are valid at a certain scale but not flexible in being scaled up or down. Data requirements, model inflexibility, and spatial considerations have all added to the challenge of the proper scale to frame multiresource research questions.

Much of the research described so far used stand-level analysis. Generalizing from stand-level analysis to higher aggregations (e.g., multistand, forests, watersheds, regions) can be problematic. The Hartman formulation focuses on multiple-use benefits on a single stand, and as such, it disregards stand interactions that are crucial to the multiple-resource problem. More recent research has examined the effects of spatial considerations on harvesting decisions. Swallow and Wear (1993) explicitly incorporated the ages of neighboring stands in a single-stand model as parameters of the amenity function to determine how stand interactions affect optimal harvest ages. O’Hara and others (1989) considered spatial constraints (such as nonadjacent harvest restrictions) on the selection of units for harvest. Hof and Joyce used a cell-based approach for spatial optimization of wildlife habitat using nonlinear programming (1992) and mixed-integer linear programming (1993). Hof and others (1994) addressed the dynamic problem of management over time (spatial and temporal optimization). Vincent and Binkley (1993) showed that the economic case for multiple-use management at the stand level is weakened when forest management decisions are generalized from a single stand to two stands. Bowes and Krutilla (1985, 1989) extended the Hartman model to the forest level, optimizing the distribution of ages. Paredes and Brodie (1989) provided a link between stand and forest-level multiple-use optimization using duality theory. Swallow and others (1997) extended earlier work to the forest level through dynamic programming. Their work supports Vincent and Binkley’s (1993) conclusion that specialized stand management may be appropriate under certain conditions. The aggregation of stand conditions over a large area can have as much impact on production as single-stand conditions for nontimber forest outputs like visual quality and wildlife (Haight and others 1992).

At the other end of the spectrum from individual resource studies are longitudinal and large-scale studies. Long-term studies like the Beaver Creek (Arizona) pilot watershed (Fox and Garrett 1989) evaluated multiple-use effects of watershed treatments. The effect of treatment levels on water runoff, sediment yield, flood magnitude, wildlife, range forage, recreational use, and scenic beauty were analyzed to produce resource response functions showing how vegetative-modification practices affect these outputs (Tecle and others 1989). Carder (1977) examined ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) studies and pinon-juniper (*Pinus edulis*-*Juniperus* spp.) treatments, and Ffolliott and Thorud (1977) showed that thinning in ponderosa pine increased water yield, but water quality deteriorated. The Hubbard Brook (New Hampshire) study area was the site of many long-range studies on water yield from different silvicultural practices (summarized in Hornbeck and others 1997).

More recent large-scale (watershed or higher) empirical studies have been initiated to evaluate multiresource management in the Pacific Northwest. Monserud and Peterson (1999) reviewed seven of these that all included consideration of joint production of wood and at least one other forest value (wildlife, aquatics, biodiversity, or social values). The studies were alternatives to clearcutting (McClellan and others 2000), Capitol Forest study (Curtis 1996, Thysell and others 1997), demonstration of ecosystem management options (Aubry and others 1998, Halpern and others 1999, Halpern and Raphael 1999), density management study (Olson and others 1999, Tappeiner and others 1999), Olympia habitat development study (Harrington and Carey 1997), forest ecosystem study in Washington (Carey and others 1999), and montane alternative silvicultural systems (Arnott and Beese 1997, Arnott and others 1995).

In addition, the Augusta Creek study (Cissel and others 1998) and the related Blue River study in western Oregon (Cissel and others 1999, Garman 1999) covered multiresource impacts under the Northwest Forest Plan restrictions. The emphasis in these management areas was to use timber harvest to create landscape patterns similar to those created in the past through fire, and monitor the effects on other resources.

Several studies have linked individual resource response models (such as range, wildlife, fish, and water models) to land change and timber inventory models at the regional and national levels. Joyce and others (1986) described a series of resource production models linked at the regional level, the Southern United States (Joyce and others 1990), and at the national level (Joyce and others 1983). Two examples of the dynamics of intertemporal decisionmaking for multiresource forest management are studies by Hof and others (1994) and Swallow and others (1997).

A common thread in forest modeling over the past 30 years has been of the large-scale, sector-level models (see Kallio and others 1987, Seppala and others 1983). The Scandinavian forest sector model (Randers and others, n.d.) used a systems approach to analyze the transition of the sector from abundant to scarce raw material availability. These models are generally not at a scale where resource interactions can be evaluated. Interaction modeling is usually at the finer stand level up to the forest level, with a few examples of broader regional analyses.

One approach to generalizing from individual studies to a broader scope is to use meta-analysis. Rather than generating original data, meta-analysis combines the results of several related independent studies to reveal regularities across studies (Cooper and Hedges 1994). Although considered primarily as a method of generating, not testing, hypotheses, meta-analysis has the benefit of testing the widespread applicability of experimental results (Hartley and Hunter 1998). Meta-analysis allows better control of Type II errors (failing to reject the null hypothesis when it is false) that have more serious consequences than Type I errors (rejecting the null hypothesis when it is true) for conservation-related decisions (Fernandez-Duque and Valeggia

1994). In other words, it is less harmful, from a conservation perspective, to conclude that there is an effect when there is not (Type I error) than to conclude that there is no effect when there is (Type II error).

Examples of natural resources meta-analysis include Wallace and Dyer's (1996) analysis of grazing effects on grassland ecosystems, Hartley and Hunter's (1998) use of meta-analysis in studies dealing with edge effect and nest predation, and Fernandez-Duque and Valeggia's (1994) meta-analysis of five studies that report data on the effects of selective logging on density of birds. Although not multiresource analyses per se, the meta-analysis of Loomis and White (1996) summarized the work that values endangered species, and Burnham and others (1996) analyzed vital rates from studies of northern spotted owl. References to meta-analysis in forestry literature are nonexistent, but the large-scale studies listed earlier may provide opportunities for extending the results of individual studies through meta-analysis.

Optimization

The PPF can be identified by constrained optimization. In the two-output case illustrated in figures 2 and 3, the optimization problem is:

$$\max T$$
$$s.t. R \geq \bar{R} .$$

The level of $\bar{R}$ is initially set to zero to estimate the maximum value for T. Then the model is repeatedly solved for incrementally increasing $\bar{R}$ until R reaches its upper limit. Variations in the two-product analysis were shown by Connaughton and Fight (1984) who demonstrated how to include a third objective in the two-dimensional PPF by calculating transformation curves between timber and owls under two different scenarios for a third resource (elk). To identify a multidimensional PPF, one output is selected for optimization, and the model is solved for a grid of levels for the remaining outputs.

When two or more objectives are not completely complementary, mathematical programming models can help quantify tradeoffs between competing objectives (Schulte and others 1999). The planning models of the 1970s and 1980s used linear programming models such as FORPLAN (Johnson and Scheurman 1977) to identify efficient land allocations on national forests. Linear programming generally replaced more simplistic cost-benefit analysis but still used simple linear approximations to represent resource interactions.

The few studies that specifically try to model the PPF for forest uses model wildlife-timber tradeoffs. Rohweder and others (2000) demonstrated the potential compatibility between timber production and elk (hiding cover), pileated woodpecker, songbirds, and insect and fire risk in the Blue Mountains of Oregon by simulating the effects of timber management on the other resources. Arthaud and Rose (1996) estimated the PPF for wildlife and timber by linking a spatial habitat suitability index model for ruffed grouse with soil expectation calculations for aspen stands using an iterative search algorithm.

In recent years, there has been notable progress in using mathematical programming methods to model the compatibility of wildlife and timber. For example, Hof and Raphael (1993) used timber age-class optimization for wildlife nonspatial optimization. Jones and Schuster (1985) used mixed-integer programming to compare five projects for the joint production of timber and elk.

Simulation models that predict impacts of management of the various resources, however, are often too complicated and time-consuming to incorporate directly into optimization models. Hof and Raphael (1997) described the difficulty and warned that because of inevitable simplifications in building any optimization model, the results must be scrutinized before conclusions are drawn. They demonstrated an approach that builds on the strengths of simulation and optimization. They used a simulation model of northern spotted owl dynamics (McKelvey and others 1992) to construct a simplified model of spatial biological processes to use in a linear programming optimization model. They solved for the optimal placement of a fixed amount of habitat on the Olympic Peninsula in the State of Washington. They then tested the optimization results in the simulation model.

Calkin (2001) followed a similar procedure to trace out the PPF for likelihood of northern flying squirrel persistence and net present value of timber harvest. He used Schumaker's (1998) PATCH model to simulate northern flying squirrel population dynamics on a changing landscape and a simulated annealing heuristic search algorithm to search for points on the PPF. Heuristic algorithms are extremely flexible, imposing no restrictions on the decision space, but they generally identify good, but not necessarily optimal, solutions. Nalle (2001) took this approach one step further by identifying a three-dimensional PPF for likelihood of persistence for two wildlife species with competing habitat needs—the great horned owl (*Bubo virginianus*) and the common porcupine (*Erethizon dorsatum*)—and net present value of timber harvest.

Valuation

Because forest decisions are societal choices, management goals must be socially acceptable. In economic models, social preferences are represented by relative values of goods. Many studies try to measure some forest uses in terms of monetary value. In some cases, the monetary value is actually intended to be an output measure (e.g., constant dollars are often used as a homogeneous measure of a heterogeneous good such as capital investment). For example, it may be convenient to measure a timber harvest schedule as the present value of timber harvested over the time horizon.

For market goods, relative values are revealed through purchasing decisions and the resulting market prices. But many forest uses are public goods (e.g., certain forms of outdoor recreation, protection of biodiversity, scenic amenities provided by forest landscapes, wildlife habitat, and watershed protection) that often cannot be provided through market mechanisms (van Kooten 1995). For this reason, some studies use market prices for market uses (e.g., timber production) but do not try to value non-market uses (e.g., biodiversity) in monetary terms (Montgomery and others 1994). In that case, the PPF is really an inverted total cost curve; its slope measures the marginal opportunity cost for the nonmonetary output in terms of the foregone value of the monetary output.

There has been considerable research on methods for valuing public goods. Information needs include appropriate units of measure, data on the biophysical yields or human rates of use (both consumptive and nonconsumptive) and price (willingness to pay) (Haynes and Weigand 1997). Methods for valuing nonmarket forest uses in monetary terms include contingent valuation, travel cost, and hedonic pricing. Valuation of nonmarket forest uses often reflects people's desire to know that rare and unique ecosystems exist (existence value), that they will be available for future visits (option values), and that they will be protected for future generations (bequest values) (Randall and Stoll 1983).

In studies that try to value both market and nonmarket forest uses in monetary terms, the optimization becomes a search for the combination of forest uses that generates the highest value:

$$\max P_T T + P_R R \, .$$

The solution is the tangency of the PPF and the price line as depicted in figures 2 and 3. The PPF can be identified by solving the model for a range of relative values, essentially changing the slope of the price line and finding new tangencies. That is the approach taken by Montgomery and others (1999).

An alternative to monetary valuation of public goods is based on the very rudiments of consumer choice theory. The economic model of consumer utility builds on the assertion that individuals can provide a complete and rational ordering of their preferences for alternative bundles of goods. In conjoint analysis, forest management scenarios are specified as alternative bundle of attributes. Individuals are then asked to rank their preferences for various alternative bundles. Studies by Zinkhan and others (1997) and Dennis (1998) use this method to measure user preferences for recreational attributes on forest lands in the former study and recreational, wildlife and timber values in the latter.

Social acceptance of forest management also depends on regional economic impacts. Niemi and Whitelaw (1999) discuss four categories of indirect costs that can explain the competitive nature of forest management decisions (i.e., determining the winners and losers in resource allocation): economic displacement costs, opportunity costs, subsidies, and environmental externalities. Pedersen and others (1989) analyze economic impacts associated with forest products, wood energy, and outdoor recreation. Three examples of policies that generated economic impact analysis are the Interior Columbia Basin Ecosystem Management Project (USDA 1996), the plan to improve Pacific salmon (*Onchorhynchus* spp.) habitat on national forest lands in the Pacific Northwest (PACFISH) (Bolon and others 1995), and the Northwest Forest Plan (Haynes and Perez 2000).

Pacific Northwest Studies

One of the objectives of the USDA Forest Service wood compatibility initiative is to evaluate the compatibility of wood and nonwood forest uses in the Douglas-fir region of the Pacific Northwest and southeast Alaska. To that end, we summarize compatibility and multiresource research set in the Pacific Northwest in this section.

The foundation for much of the interdisciplinary analysis of timber harvesting effects on other resources in the Pacific Northwest has been done by scientists who have identified and described the relations among the plants, animals, and other components of the forest ecosystem of the region. One recent example is a paper by Carey (1995) describing the relations between the northern spotted owl, three western Oregon and Washington squirrel (*Ammospermophilus* spp.) and chipmunk (*Tamais* spp.) species, and fungi. Thomas (1979) for the east side of the Cascades Range and Curtis and others (1998) for the west side, provided guidance to land managers for managing for multiple objectives in Washington and Oregon. Both publications integrated the most current science into application guidelines. Huppert and others (1985) and Chamberlin (1982) similarly summarized management considerations related to anadromous fish habitat.

Many studies done in the Pacific Northwest have dealt with the impacts of new (and sometimes older but neglected) forest practices. Hansen and others (1991) used a simulation model for the Cascade Range in western Oregon to test the wildlife response to tree retention and longer rotation ages. Curtis and Carey (1996) reviewed the science supporting various management options for the Douglas-fir region including selection harvesting, extended rotations, biodiversity pathways, natural reserves, and intensive timber management. McComb (1993) simulated the impact of long rotations in the Douglas-fir forests of the Pacific Northwest on late-seral wildlife habitat.

Calish and others (1978) incorporated the Faustmann optimal rotation formula for soil expectation value and empirical data for nontimber yield functions for trout, nongame wildlife, visual aesthetics, deer, elk, and water yield for PNW Douglas-fir forests in the Pacific Northwest. Applying the method suggested by Hartman (1976), they found that when nontimber outputs are considered, given their nontimber valuations, there is little effect on optimum rotation length. The more qualitative integrated multi-resource model for southeast Alaska developed by Fight and others (1990) found its use primarily as a conceptual model of timber-water-fish-deer interactions.

The production possibilities frontier study of Rohweder and others (2000) found incompatible relations between timber harvest and other resources (elk hiding cover, pileated woodpecker presence, and songbird densities) to be rare in inland Pacific Northwest forests. Competitive or compatible relations between timber and other resources appear to be the rule.

Montgomery and Brown (1992) proposed a marginal economics approach to evaluating alternative conservation strategies for the northern spotted owl survival and executed it in Montgomery and others (1994). They estimated the PPF between annual federal timber harvest and probability of northern spotted owl survival using an expert opinion survey in Montgomery and Brown (1992) and an owl population simulation model in Montgomery and others (1994). The marginal cost curve for northern spotted owl survival was estimated by using a wood products market model (TAMM) to value the foregone federal timber harvest required to achieve different levels of certainty of survival. Finally in a third study, Montgomery (1995) used the approach for policy analysis to evaluate the cost of imposing the “well-distributed” requirement in the NFMA on northern spotted owl habitat. This is an example of using the PPF to demonstrate the potential inefficiency of current policy as relates to the two forest uses modeled.

Calkin (2001) also modeled the PPF explicitly, using heuristic optimization methods to model tradeoffs between timber production and probability of persistence for the northern flying squirrel (a species that prefers old forest) on a 10 000-ha landscape on the central western slope of the Cascade Range of Oregon. His model was spatially and dynamically explicit. In a related study, Nalle (2001) expanded the study area to a 1.7 million-ha study area on the western central Cascade Range of Oregon and constructed the three-dimensional PPF for timber production and two wildlife species with differing habitat requirements—the great horned owl and the common porcupine. In both studies, land management options were unconstrained in the PPF analysis, and a special case was modeled and evaluated in relation to the PPF. Calkin (2001) evaluated a simple reserve system. Nalle (2001) evaluated the inefficiencies (in relation to the forest uses modeled) of the current landownership pattern with its associated pattern of limitations and divergent objectives.

Hof and Raphael (1993) and Bevers and others (1995) used mathematical programming methods and data from 92 vertebrate species to find optimum allocations of forest age-class distributions to meet conservation objectives specified alternatively as the maximum attainable sum of the viabilities (expected species richness), the maximum attainable product of the viabilities (which they called an "equity" measure), and the maximum minimum viability in the set. These studies did not evaluate tradeoffs between conservation and biodiversity. However, they provided the foundation for later studies that did. Shunk (2000) measured the marginal opportunity cost of increasing overall biodiversity (measured as weighted expected species richness for 196 terrestrial vertebrate species) from a market base case scenario set in the Muddy Creek Basin in the Oregon Coast Range. He also demonstrated tradeoffs between conservation based on overall biodiversity and conservation based on a subset of threatened and endangered species. None of these studies were spatially explicit; species viability depended only on aggregate habitat. In a related study, Lichtenstein (2001) used heuristic optimization methods to construct a PPF for timber and overall biodiversity, also measured as expected species richness for terrestrial vertebrates, in a spatially and dynamically explicit model. Adjacency of suitable habitat mattered for species with large home range requirements. Like Nalle (2001), Lichtenstein (2001) ignored the pattern of landownerships and differing landowner objectives during the construction of the PPF and then evaluated a special case scenario in which the landownership pattern was imposed. The scenario analysis suggested that there might be opportunity for managing the study landscape for more timber and more biodiversity.

Adams and others (1992) and Alig and others (1992) used habitat suitability indices for selected species to test the effects of various harvesting scenarios for western Washington on species habitat preferences. They found that, given the projected harvest patterns, indices for species with strong preferences in the grass-forb to open sapling-pole stages (such as black-tailed deer (*Odocoileus hemionus*), voles, mice, and shrews) generally show a steady decline over the projection period (to 2090). Species that strongly prefer the large sawtimber-old growth conditions (such as flying squirrel (*Glaucomys sabrinus*) and pileated woodpecker) showed a rise or initial decline followed by a rise. Species with mixed preferences for old-growth and younger stands (like ruffed grouse and sharp-shinned hawk (*Accipter striatus*) show a decline or small initial rise followed by a decline.

Mendoza (1988) similarly simplified the habitat requirements of six indicator species in western Washington and used multiobjective programming to optimize for returns from timber management and a total utility index for each wildlife species under various management regimes. The analysis allowed planners to compare scenarios based on the success of individual species in a multiple-species environment.

Lippke and Oliver (1993) discussed the contrasting approaches to preserving biodiversity and creating wildlife habitat through "natural reserves" and through landscape management. They argued that separate production implies that many acres set aside will be in reserves and will not produce any timber-market values, thus forcing a shift to less efficient, more costly sources of wood and substitutes. Managing other areas for timber alone supports only a limited spectrum of wildlife. They argued that managing to support more diverse habitats while harvesting timber to help pay for operations can reduce the cost of producing both outputs. Lippke and others (1999) used simulations similar to Adams and others (1992) to show that regulatory approaches that rely only on no-management set-asides to retain the forest structures that are in declining supply are more costly and take much longer to produce equivalent levels of late-seral stand structures important to endangered species. If active management approaches can restore forest structures that are in decline in a shorter period, then management alternatives are substantially less costly than regulatory set-asides in restoring habitat.

Parks and Murray (1994) recognized that the flow of benefits from forest environments depends on both the extensive margin—how much land is devoted to forest use and the intensive margin—how the land devoted to forests is used. Most studies address the intensive margin. Parks and Murray's study of the Pacific Northwest land use allocation addressed the extensive margin.

Fight and Randall (1980) used data from the Mount Hood National Forest in Oregon to estimate the cost of enhancing visual quality. The increase in management costs (as opposed to opportunity costs for foregone harvest volume) was calculated under two visual scenarios and showed a 14-percent rise in costs for the higher visual management standard.

As mentioned in the previous section, many recent large-scale applications of the science related to resource interactions have been initiated. The large integrated ecosystem management studies (Monserud and Peterson 1999) and the Blue River project (Cissel and others 1999, Garman 1999) will provide validation of multiresource management effects for many years to come.

Wildlife and biodiversity concerns have increasingly driven forest policy and public forest management in the Pacific Northwest in the last decade. So it is not surprising that, with few exceptions, these studies analyzed the impacts of timber harvest on individual wildlife species viability or on biodiversity as a function of individual species viabilities using various simulation and optimization techniques. Some studies simulated the effects of management for wildlife on future stand conditions (Bevers and others 1995, Hof and Raphael 1993, Lippke and others 1999) or vice versa (Adams and others 1992, Alig and others 1992, Hansen and others 1991, McComb 1993, Mendoza 1988). But some look at marginal tradeoffs between timber production and wildlife conservation on the efficient frontier either explicitly using optimization or implicitly by assumption (Calkin 2001, Lichtenstein 2001, Montgomery and others 1994, Nalle 2001, Rohweder and others 2000, Shunk 2000,). With the exception of the summary management guides (Curtis and others 1998, Thomas 1979), few studies used site-specific analysis but rather were mostly analyzed at the regional level. Most studies had an economic component usually computed from harvest volume projections—thereby estimating the opportunity cost of managing for the wildlife. Those studies that explicitly measured the tradeoffs between timber and other values and products failed to find incompatibility.

Conclusion

Among the important themes that the wood compatibility initiative was meant to address, three multiresource questions can be raised vis a vis existing research:

1. Are management guidelines being developed to aid managers in implementing joint production research findings? Although there are some excellent examples of documents summarizing recent research for use in developing management guidelines (Curtis and others 1998, Thomas 1979), most of the examples in them come from single-resource research. The joint production research to aid in developing management guidelines has been missing or too theoretical to have application for the land manager. No meta-analysis work has been reported in the forestry literature, but there seems to be promise in analysis from the many thinning studies done in the Pacific Northwest. These have the potential to glean general management guidelines from specific studies.

2. At what scale are we best prepared to understand tradeoffs between wood production and other forest products and values? Although most of the single-resource research has occurred at the stand level, most of the explicit tradeoff research has been done at highly aggregated regional levels. Although useful at the regional policy planning level, this information is not very useful for management prescriptions.

3. To what extent has multiresource research shown the production of wood to be compatible with the production and sustainability of other resources? The studies that have directly addressed this question have generally found compatibility or competition between timber and most other resources but only rarely incompatibility. In terms of the production possibilities frontier graphs shown earlier, joint production studies have shown production relations to be similar to figure 2 rather than figure 3. This result should be qualified by reference to the geographic scale of the analysis. As noted earlier, forest uses are more likely to be compatible at the regional or forest scale than at the smaller stand or management unit scale. Also, in most of the studies reported, the analysis is not spatially explicit. When spatial habitat considerations are modeled (such as contiguity and connectivity), there will be less flexibility in the location of habitat for some species, and one might expect less compatibility with wood production.

There has been a cyclic pattern to wood compatibility research. This pattern can be traced to changes in legislative mandates and administrative direction (as translated into research funding) as well as the inevitable ebb and flow of research interest. Although there is continuing interest in interdisciplinary research, it is not apparent that the barriers (budgetary, institutional, or otherwise) to interdisciplinary research are sufficiently low enough to encourage an increase in activity. This is problematic because relations between scientists from different disciplines must be developed and nurtured by ongoing and consistent conversation over time for collaboration across disciplines to be productive. It is simpler for scientists to isolate themselves in their own disciplinary niche and speak only with one another than to undertake the frequently frustrating task of trying to communicate in an environment in which the mundane working language of one discipline arouses passions in members of another discipline. But the pressing question of the allocation of scarce resources cannot be answered without cooperation and communication across disciplines. And such cooperation will require stable and ongoing support from the relevant research institutions and resource management agencies.

One of the objectives of this study was to explore the existing body of research for work that could guide practicing forest managers in developing efficient on-the-ground management plans now. Our findings are disappointing in that much of the existing compatibility research is conceptual in nature; its primary purpose was to demonstrate methods and ideas. There have been few empirical production studies and none for the Pacific Northwest region in over 20 years. Although there are many general multiresource models, including some cutting-edge optimization models, few lend themselves to empirical application. That situation, however, is changing. Advances in the knowledge base, computing technology, and modeling skills necessary to model forest resource uses and interactions in a spatially and dynamically explicit manner will make it possible to present land managers with a range of credible, feasible, and efficient forest management options (efficient in the sense that they approach the productive capacity of a site given the framework of constraints within which the land managers must operate). One promising area of inquiry is in the recent application of production possibilities frontier work, especially in relation to wildlife-timber tradeoffs.

The compatibility framework also lends itself to policy analysis. Most impact assessment studies were constructed specifically for policy analysis; prospective policy scenarios were simulated, and impacts on forest uses and the state of the forest resource were reported (RPA assessments, for example). These models are “positive” in the sense that they simulate likely outcomes. Production possibilities frontier studies can be “normative” in the sense that an efficiency standard is posed by which policy scenarios may be evaluated. The unconstrained PPF sets the outer limits on what is possible on a landscape in relation to the forest uses that are modeled. But forest managers are subjected to an array of constraints arising from budgets, infrastructure, and regulations. Also, private and social objectives for forest land do not necessarily coincide. Society as a whole may desire a balanced mix of commodities and environmental services from forest land. But private landowners responding to market incentives have no reason to produce that mix, and public agencies must respond to political mandates driven by interest groups that may not represent society as a whole. A few compatibility studies examine inefficiencies, searching for policy scenarios that might allow for unambiguous gains—more timber and more conservation. Examples include Bare and others (2000), Lichtenstein (2001), and Shunk (2000). The methods developed in these studies can be refined and generalized so that they might be applied to a broad array of forest resource conflicts—guiding policymakers in the search for policies that are likely to “pay off.”

We are less optimistic about the potential of multiresource research to guide policymakers in identifying the "best mix" of forest uses or even in determining whether a shift from one mix of uses to another is desirable. That requires relative values for all relevant forest uses, including nonmarket uses such as biodiversity, aesthetics, and conservation of a natural heritage. Consequently, much of the best compatibility research has placed a monetary value on market uses (usually timber production) and a quantitative assessment of risk for the environmental amenity (e.g., viability for wildlife species or expected number of species for biodiversity).

One of the primary objectives of forest management is to meet the needs of the landowner. This may be profit maximization for the industrial owner, aesthetics for the exurban small nonindustrial forest owner, or various protection and consumptive uses for the public landowner. But no matter what the landowner objective, an implicit belief has always been that multiple resources were being produced. As the research described here has shown, it is difficult to model true joint production of multiple resources. Incompatibilities of scale, time, data, method, and degree of detail have made integrated multidiscipline, multiresource research an elusive goal. In spite of the difficulties, this research has provided and will continue to provide useful insights into the nature of and possibilities for multiresource forest management.

English Equivalents

1 billion board feet = 5.66 million cubic meters
1 hectare (ha) = 2.47 acres

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