AN ABSTRACT OF THE THESIS OF

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Analysis of import trade since 1976 shows that forests of the Pacific Northwest provide Japan with the largest share of pine mushrooms (*Tricholoma* spp.) outside of East Asia. To determine whether North American pine mushrooms (*Tricholoma magnivelare* (Peck) Redhead) merit more intensive management in the southern Cascade Range, a major center of commercial harvesting, the bioeconomic model MUSHROOM has been developed. The model links annual pine mushroom crops to joint production of other timber and non-timber forest products at the Diamond Lake pine mushroom management area in the Umpqua National Forest, Oregon. Experimental silvicultural regimes emphasize growth of major tree species hosting pine mushrooms plus the major timber species, western white pine (*Pinus monticola* Dougl. ex D. Don), for creating mixed-species, uneven-aged forests with old-growth retention trees. Silvicultural scenarios are evaluated for feasibility on the basis of statistical distributions of financial returns from forest products during a 25-year planning period.

Early partial timber harvests offset costs of management designed to promote larger pine mushroom crops. Stands with numerous, large Shasta red firs (*Abies magnifica* A. Murr. var. *shastensis* Lemmon) are most likely to produce highest incomes from pine mushroom management initially. Conversion of young stands with few tall overstory trees or of stands dominated by Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) incur the greatest costs for stand conversion to create pine mushroom colonies. Bough pruning to reduce stand leaf area is designed to improve the understory environment for pine mushrooms, but commercial conifer bough sales from pruned boughs may not compensate for pruning costs. Cones of pine species contribute more to stand income than do pine mushrooms in stands having few true fir or mountain hemlock (*Tsuga mertensiana* (Bong.) Carr) overstory trees. A survey of new directions for research, modeling capability, and management points to the need for better understanding of links between weather events and mushroom production, for better data about transfers of water and energy through tree canopies and through ash and pumice soils, and for a labor force trained to monitor and tend pine mushroom colonies.

Keywords: *Abies amabilis*, *Abies magnifica* var. *shastensis*, agroforestry systems, bioeconomic models, Cascade Range, Christmas trees, decorative boughs, Diamond Lake, matsutake, net present value, non-timber forest products, Pacific Northwest, pine cones, pine mushrooms, *Pinus contorta*, *Pinus monticola*, *Tricholoma magnivelare*, *Tsuga mertensiana*.

Forest Management for the North American Pine Mushroom (*Tricholoma magnivelare* (Peck) Redhead) in the Southern Cascade Range

by

James F. Weigand

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

Er will gleichsam den Wald, und der andere die Bäume; und Wald, das ist etwas schwer Ausdrückbares, wogegen Bäume soundsoviel Festmeter bestimmter Qualität bedeuten.

Robert Musil, *Der Mann ohne Eigenschaften*

Haben Sie schon gesehen, in was für Figuren die Schwämme auf dem Boden wachsen? Wer das lesen könnt!

Georg Büchner, *Woyzeck*

Forest Management of the North American Pine Mushroom (*Tricholoma magnivelare* (Peck) Redhead) in the Southern Cascade Range

1. Introduction

Societal perceptions about the range of possible commercial products from federally managed forests in the Pacific Northwest are broadening the number of resources for which forest managers must account. The call for multiple-product forest management comes at the same time that staffs and programs for public land management are being cut for the sake of reduced governance. Managers are obliged to assign ever scarcer funds to resources that hold the most promise for increased financial returns. Uncertainty about how to allocate resources to best meet expectations of society is confounding managers. Information is wanting for many of the products increasingly demanded. At the same time, hesitancy on the part of management to act without policy guidance or supporting information may only exacerbate the gap between forest management and societal expectations. This thesis provides an example of one way to overcome limitations of poor or missing information and to make timely policy choices.

Historically, managers have dedicated funds for resource development in public forests to a single commercial product, timber. The tradition reflects two assumptions central to the North American philosophy of sustainable use (Garrett and Buck 1997, Vincent and Binkley 1993) :

- land serves society best by producing benefits efficiently and that efficiency is the maximum sustainable economic rent, and
- efficiency is achieved most easily when land is apportioned to yield rents from single, discrete uses.

Federal forest planning has conventionally delimited forested land into portions designated principally for timber production (the timber land base) and portions for recreational, aesthetic, or biological amenities (National Parks, Wilderness Areas, and

Research Natural Areas, for example). High volume and value of wood production from many forest types in the Pacific Northwest and the additional employment from value-added processing make timber an attractive product from Federal lands. On the other hand, forest lands designated for amenity uses generally have low timber productivity and generates little income for Federal forest management.

Public concern for amenity values has grown particularly as the supply of old-growth forest ecosystems has become scarce, and the conflict in values has sharpened between conserving amenity values and producing timber outputs. Efforts to redirect public forest management in the Pacific Northwest such as the President's Forest Plan for the Pacific Northwest (Forest Ecosystem Management Assessment Team 1993, U.S.D.A. Forest Service and U.S.D.I. Bureau of Land Management 1994) may reduce timber outputs, revenues, and timber-based employment from public forests permanently. Re-examining production possibilities for public forests, however, may uncover leeway that recoups at least part of the lost value from timber production and reconciles societal demands both for intact forests and for forests that produce high-value commercial goods.
A key question for public forest managers is where funds are best invested to increase commercial production and revenues accruing from public forests in an increasingly constrained environment for timber production. Four options for resource investment are available: continue investment in timber alone; dispense with investment to timber and focus on one or more non-timber forest products; invest in both timber and non-timber forest products jointly; or suspend any investment altogether. Phrased differently, are there ways to retain the forest canopy structure while harvesting sustainably commercial non-timber forest products in the understory with or without intermittent timber harvests? The extent to which each of the four investment options is appropriate in the public forest landscape of the Cascade Range and elsewhere in the Pacific Northwest is poorly understood.

Management agencies also need to clarify to society the scope of beneficiaries resulting from shifts to joint production. In particular, is the goal of increasing joint production to stabilize or increase economic benefits to the federal land management agency or to all of society? Conflict arising from allocating benefits may worsen if the U.S. Congress requires that land management agencies raise their own funds to pay for basic ecosystem management. If, on the other hand, economic benefits are maximized ultimately for net benefit to all of society, the agency must define its responsibility and commitment for regulating intensified extraction to ensure the continued productive capacity of the environment and to distribute economic benefits to society in a socially-acceptable manner.

Joint production of resources is attractive from a societal standpoint because joint production emphasizes resource compatibility rather than resource competition to derive income from forest landscapes (Pacific Northwest Research Station 1997). A tradition of joint production of goods through forest management in the Pacific Northwest has not developed since Euro-American colonization began more than 150 years ago. The store and value of regional timber resources were stunning. New settlers, with inherited agrarian or resource-mining traditions, did not adopt or adapt joint production systems practiced by indigenous peoples in forest and savanna woodland ecosystems of the Pacific Northwest (Boyd 1986, Gottesfeld 1994).

In other regions, where timber resources are not particularly valuable, joint production has assumed greater significance in management. Bowes et al. (1984), for example, make a case for landscape management with joint production of timber and water resources in the Colorado Rocky Mountains. A single focus on either resource alone in a financial analysis precludes against resource development and extraction. The low timber value of native tree species and naturally slow tree growth make management based on timber alone uneconomical. Timber receipts do not cover the cost of road access to remote high-elevation forests. Admitting values into the production equation from increased production of water runoff changes the economic feasibility. Greater snowmelt resulting from timber harvests in high-elevation forests provides more runoff water for hydropower generation, agricultural irrigation, and drinking water for people living at lower elevations. Increased water volume compensates for the deficit from road building. In this instance, linked management reinforces development of both resources and provides greater net present value than either no management or single resource management.

In contrast to the study by Bowes et al. (1984), this thesis addresses joint production possibilities in high-elevation forests at the stand scale and over a much smaller area: the high-elevation forests of the ash and pumice deposition zone in the vicinity of Crater Lake in the southern Cascade Range. The harsh climate and skeletal volcanic soils impede rapid tree growth. Fungal and plant parasites also reduce tree productivity and have decimated native populations of the most valuable timber species in the area, western white pine (*Pinus monticola* Dougl. ex D. Don). Plant species diversity is also uniformly low among the plant associations found in the area (Atzet et al. 1996).

With this apparently inauspicious environment as the subject, I propose that a directed method of inquiry may reveal new options for forest management and resource development. Opportunity for improving financial returns may be greatest precisely in these timber "wastelands" in the southern Cascade Range. Matching forests with low timber production to one or more high-value non-timber resources may require new management aims and practices.

Methodical inquiry into central issues of management for non-timber forest products has thus far been missing in the Pacific Northwest forest science research, although the region is primed for development of these resources (Garrett and Buck 1997). In this thesis, I use as a framework for analyzing forest management a systems construct of agroforestry joint production, in particular that of forest farming. Agroforestry systems are frequently used as tools for rural development, but in North America, agroforestry systems in native forests are rare. Other societies, however, have consciously included forest farming as a part of total forest planning. The former Soviet Union, for example, included forest food production as part of an integrated national food production program (U.S.S.R. Ministry of Forest Industries and Management 1983).

This thesis addresses the particular problem of resource management for North American pine mushrooms (*Tricholoma magnivelare* (Peck) Redhead) in the southern Cascade Range. Emphasis on multiple products invites options for removing smaller amounts of biomass from the understory or from the canopy at frequent intervals while maintaining the physical structure and biological function of forests. Pine mushrooms are attractive as a high-value resource from a small amount of biomass. They also occur frequently at sites where timber productivity is low. Smoothing the temporal flow of valuable economic production from sites with low rates of biomass (or timber) production can diminish the financial incentive to harvest timber in ways counter to patterns emulating natural forest disturbances. Low timber productivity need not imply foregoing forest management on some sites. A shift in silviculture for joint forest production with pine mushrooms and timber focuses on increasing total income rather than producing timber harvest targets.

Before a comprehensive analysis of new production possibilities can begin, existing background information about potential products, biological constraints, ecosystem processes, suitable management practices, and likely output quantities need to be assembled and organized (Taylor 1995). Without supporting documentation and analysis, land managers cannot evaluate the feasibility of investments in multi-product agroforestry at high elevations in the southern Cascade Range. I suggest an organized process based on interdisciplinary analysis to gain quickly an overview of issues related to pine mushrooms. Key steps in the process are:

- Document the human behavior that compels the need to manage pine mushrooms;
- Acquire information about markets for pine mushrooms, including prices, supply,

and demand;

- Gather known data about production of substitutable or linked resources;
- Organize existing information into a bioeconomic model;
- Develop scenarios of management practices, biological production, and future economic value for pine mushrooms and other resources linked in joint production;
- Simulate futures based on existing data and explicitly defined assumptions; and
- Analyze results of scenario simulations for least risk and greatest financial return as a basis for management decisions.

This process for analysis has obstacles. Historical preference to develop timber resources has created considerable knowledge about timber production and timber market economics. The result is a balance of knowledge weighted heavily to commercial timber tree species and contrasting with a near void of information about commercial products from species found in forest understories. Public land management agencies have made fleeting attempts to chronicle biological production, commercial extraction, and consumption of non-timber forest products from Pacific Northwest forests in the past (von Hagen et al. 1996), but forest management has much catching up to do. Knowledge about production functions of understory species, sustainable harvest methods, product demands, and the populations of gatherers is needed. What knowledge exists is poorly organized or inaccessible to forest managers. Interdisciplinary efforts to draw upon the knowledge of pickers, processors, and scientists have been absent with a few notable exceptions (for example, Schlosser and Blatner 1995, 1996) to date.

This thesis introduces the problem of pine mushroom management as one rooted in human behavior. Human behavior expresses itself in at least three ways with regard to pine mushrooms:

- in the profound fondness and hence high demand for pine mushrooms in Japan;
- in the response by pickers to price signals to supply mushrooms from the Pacific Northwest for export to Japan; and

- in the consternation of law enforcement officers, land managers, and pickers about the accelerating harvest rates and about useful responses to societal concerns about resource sustainability.

Chapter two provides an overview of the market trends for pine mushrooms. Pine mushrooms have been an important symbol in Japanese culture. Reverence for its flavor is akin to the French and Italian predilection for truffles. Natural stocks of pine mushrooms in Japan have declined markedly since 1950, and current total Japanese national consumption of pine mushrooms lies below consumption in the early 1950s. Acceptance of North American pine mushrooms by the Japanese public beginning in the 1970s led to a rapid rise in their value and has prompted many, often economically marginalized, people in the Pacific Northwest to harvest pine mushrooms commercially. The transition from a wild-growing food crop to a cultured and tended food crop in managed forests, as practiced historically in Japan and Korea, has yet to occur for pine mushrooms in the Pacific Northwest, however.

Wood fiber production coincides with pine mushroom harvests, but the manner and degree of timber harvests that promote pine mushroom production in forest types at high elevations in the southern Cascade Range are not fully known. Varying the assumptions about biological production of pine mushrooms in response to silvicultural management and timber harvest is key to testing the robustness of pine mushroom harvesting under conditions of uncertainty. On the economic side, chapter three develops future lumber price projections from which stumpage prices may be calculated. The chapter provides an analogous role to chapter two - forecasting future lumber prices by species and lumber grade from which comparisons of financial outcomes of scenarios may be compared. Of particular importance here are the projections for five species: Pacific silver fir (*Abies amabilis* Dougl. ex Forbes), Shasta red fir (*A. magnifica* A. Murr. var. *shastensis* Lemmon), lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *murryana* Engelm.), western white pine (*P. monticola* Dougl. ex D. Don), and mountain hemlock (*Tsuga mertensiana* (Bong.) Carr).

Building a computer model is a vehicle for integrating information in this thesis about biological production and price forecasting. Modeling non-timber forest products in the Pacific Northwest is provisional and even improvisational at present, but the process of modeling aids learning. Confronting knowledge gaps during modeling is a way to clarify priorities for policy-oriented research. Chapter four in the thesis documents a prototype bioeconomic model MUSHROOM for linking management practices to information about production and product prices. Documentation for the model makes plain the model structure and underlying assumptions. Where possible the model uses processes and where necessary uses empirical relations. Modularity in the model helps managers to add, delete, and improve submodels as new information becomes available from scientific and social research and from management experiments. Also, people can extract portions for incorporation into new models. The model encompasses five forest products: timber, pine mushrooms, conifer boughs, Christmas trees, and pine cones. Simulation of agroforestry systems models stand development and economic production in forests near Diamond Lake, Douglas County, Oregon.

Three stands from the Diamond Lake Ranger District furnish examples for analysis of the range of ecosystem conditions, but conclusions reached in the analysis may be relevant to similar sites in the southern Cascade Range of Oregon and California. Chapter five proposes site-specific management scenarios for the three stands based on existing silvicultural and mycological knowledge. The scenarios incorporate experimental design to simultaneously increase the value of commercial biomass produced and accelerate technical knowledge about processes affecting production of the jointly produced goods under consideration. Adjustment and replication of the scenarios regionally is encouraged. To facilitate transfer for replication, I describe the details of management in full.

Data, tools, and management scenarios developed in chapters two through five converge in chapter six for a sensitivity analysis of the quantity and value of forest production to key economic and managerial variables. Key variables include species-specific timber price forecasts, Japan per capita income, annual North American production of pine mushrooms, frequency of bough pruning, and differing hypothetical responses in pine mushroom production to silvicultural regimes designed to increase commercial production. A planning horizon of 25 years is used to examine the robustness of desired outcomes to as yet unrealized management options for joint production under stochastic natural stand regeneration and tree growth. The measure of preference for management regimes or for no management is expressed as net present value of forest products under three different discount rates. Benefits, risks, and tradeoffs are set forth from which forest managers can base decisions to proceed, to rework, or to discard scenarios. Both non-parametric and parametric statistical analyses are used to clarify the implications of forest stand management scenarios.

The thesis concludes with a summary of critical points from the initial round of policy simulations. The point cover directions for improving future agroforestry management, ecosystem modeling, and policy analysis. Specific needs for increasing knowledge and the rate of knowledge acquisition about the physiology and ecology of pine mushroom and host trees are highlighted. General needs for protocols to collect and to link sets of time-series data and to create, maintain, and improve analogous integrated bioeconomic models apply to policy analyses undertaken by public land management agencies. The third general theme of the summary chapter treats the development of appropriate institutions for modeling, validating models through monitoring, conducting issue-driven policy analyses, and organizing rights and access to non-timber forest products in stands with intensified agroforestry management.

The present process and bioeconomic model used in the thesis for policy analysis omit important topics. Considerations and models for wildlife habitat suitability and for eventual climate change are not treated, for example. Cumulative effects and emergent properties of multiple adjacent stands under pine mushroom management in watershed and landscapes are also not dealt with. These omissions underscore the need for ongoing improvement in this management model and for linkages to planning models at larger spatial scales. The process of policy-relevant analysis here also suffers from ultimately inefficient and insufficient learning by a single person working largely alone to respond to a complex policy issue. Any errors of omission or commission are mine.

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2. The Role of the Pacific Northwest in the International Trade in Pine Mushrooms

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Abstract

The North American pine mushroom or matsutake (*Tricholoma magnivelare* (Peck) Redhead) is economically the most important edible wild mushroom species in the Pacific Northwest. Most production is destined for Japanese markets. Analysis of trade data on imports to Japan since 1976 demonstrates that supplies from the Pacific Northwest provide the largest share of pine mushrooms outside of East Asia. Increased consumption in Japan of pine mushrooms from the Pacific Northwest correlates with the rise in disposable income in Japan. Prices for Pacific Northwest pine mushrooms, based on differing assumptions of future per capita income in Japan, are projected to the year 2020. Real prices for pine mushrooms are likely to increase as long as the Japanese economy grows at even a modest (1.5%) annual rate over the next 20 years. More intensive production of pine mushrooms in the region, particularly in privately-owned forests, can increase the volume of pine mushrooms for export. Measures proposed for achieving higher pine mushroom harvests are: targeting forest types best suited to management for enhancing commercial yields, developing agroforestry systems appropriate to conditions in productive stands, and market research and marketing to expand consumption in East Asia and North America.

Additional Key Words: British Columbia, matsutake, Oregon, *Tricholoma matsutake*, Washington State.

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2.1. Introduction

Public awareness of the potential for developing forest fungi resources in the Pacific Northwest region has increased steadily over the last two decades (Amaranthus and Pilz 1996). At the same time, management and investment for these resources has lagged behind. Information about markets for edible wild mushrooms is essential to clarify direction in forest management and to allocate expenditures for producing socially desirable goods and services. The trade in North American pine mushrooms, also known as American matsutake, (*Tricholoma magnivelare* (Peck) Redhead) is particularly significant in the Pacific Northwest. This article continues work initiated by Schlosser and Blatner (1995) and Meyer Resources, Inc. (1995) to characterize the market for pine mushrooms and identify the economic costs and benefits to forest-based economies in the region for developing pine mushroom resources. After providing an overview of international pine mushroom commerce, I describe an econometric model for pine mushroom production and export in the Pacific Northwest for the period 1976-1995, develop scenarios for price projections to 2020, and conclude with a discussion of implications for investment in future production of pine mushrooms from the region.

The suite of species included under the rubric pine mushrooms or matsutake belongs to the family Tricholomataceae, genus *Tricholoma*, subgenus Tricholoma, section Genuina, and branch (*stirps*) Caligatum (Singer 1986). They share common features of morphology, autecology, biochemical production, mode of basidiospore germination, fragrance, and culinary use (Iwase 1994, Ogawa 1979, Ogawa and Ohara 1978, Ohara and Ogawa 1982, Singer 1986). At least four species are commercial: *T. matsutake*, the most important species in East Asia, *T. bakamatsutake* Hongo, also from East Asia, *T. magnivelare* from North America, and *T. caligatum* from North America, Eurasia, and North Africa.

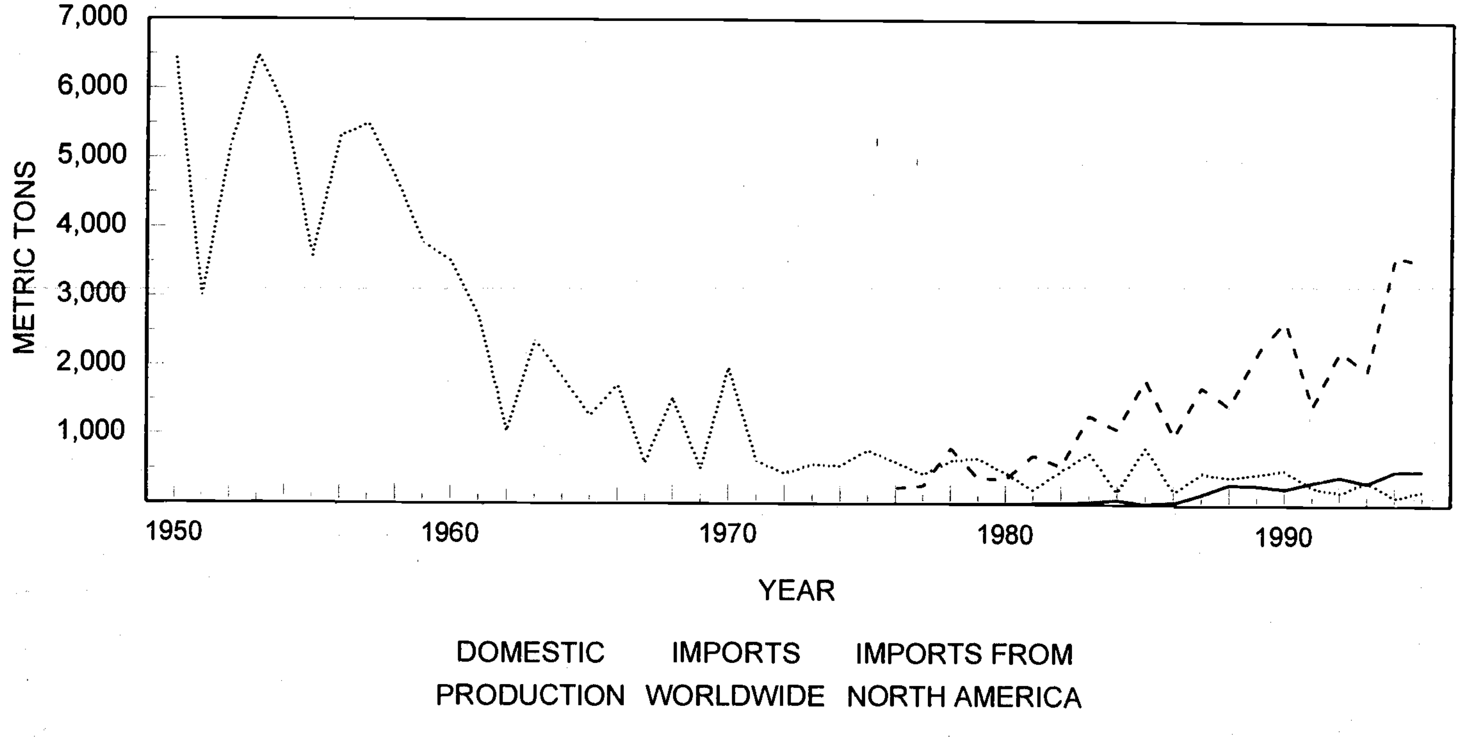
2.2. The Market for Pine Mushrooms

Japan is the major market for pine mushrooms. For more than a millennium, pine mushrooms have been part of Japanese cuisine (Hosford et al. in press). Pine mushrooms are appreciated for their association with the autumn season, their aesthetic appearance, texture, and fragrance. In a survey of residents in major Japanese urban centers, pine mushrooms ranked third overall in popularity among edible mushrooms, with 86% of respondents stating a preference for them (Sugiura and Kishimoto 1989). Their high price, however, is prohibitive for many people.

Both domestically produced and imported pine mushrooms are consumed in Japan. For the period 1991-95, Japanese production comprised from three to sixteen percent of total national consumption. Changes in forest management practices (Kawai and Ogawa 1981) and prevalence of insect and nematode pathogens (Hosford et al. in press) have created less favorable conditions for *T. matsutake* in stands of Japanese red pine (*Pinus densiflora*), the major host tree species in Japan forming mycorrhizal connections between tree roots and fungi mycelia. Japanese production plummeted after 1960, and since the mid-1970s, production has remained at one-tenth or less of the annual harvest quantity in the early 1950s (figure 2.1.). Today, even with import quantities rising, total pine mushrooms available to the Japanese market do not exceed production levels in Japan alone during the 1950s.

Unlike most other popular edible mushrooms in Japan, pine mushroom species are obligate mycorrhizal partners with living trees. Success in culturing *T. matsutake* artificially to obtain commercial quantities has thus far eluded researchers (Inaba et al. 1995, Iwase et al. 1988). Commercial stocks of pine mushrooms are available only from forest stands where microsite conditions favor pine mushroom fruiting. Both Korean and Japanese forest scientists have developed regimes for vegetation management to foster pine mushrooms in red pine forests (Ogawa 1982). Despite ongoing efforts to culture

Figure 2.1. Japanese pine mushroom production and imports, 1950-1995.



Sources: Japan Ministry of Agriculture, Forests, and Fisheries
Japan Tariff Association

pine mushrooms in forest settings, pine mushrooms remain a tiny fraction (0.63%) of the total commercial production of edible fungi species in Japan (Jäppinen 1987).

Economic prosperity coupled with the decline of domestic harvests has spurred growth in Japanese markets for imported pine mushrooms. In response, foreign sources developed, first in South Korea by 1967 (Sung and Kim 1991) and then in North America by 1976. The Japan Tariff Association has maintained records of pine mushroom imports to Japan since 1976. This twenty-year record provides data for econometric analysis here. Beginning in 1993, data on edible mushrooms imports to Japan have been further divided to account for shiitake and truffles. Table 2.1. shows the volume and value of imports of pine mushrooms compared to other edible mushrooms since 1993.

Table 2.1. Value and volume of Japanese imports of fresh and chilled mushrooms, 1993-1995.

	Value in billions of constant 1990 ¥			Volume in metric tons		
Species Group	*1993*	*1994*	*1995*	*1993*	*1994*	*1995*
pine mushrooms (*Tricholoma spp.*)	13 309	19 262	20 136	1 943	3 622	3 515
shiitake (*Edodes lentinus*)	9 316	10 456	9 608	15 586	24 316	26 308
truffles (*Tuber spp.*)	253	289	344	4	5	5
all other species	240	266	340	436	655	572

Source: Japan Tariff Association (1976-1995), commodities 0709.51-010, 0709.51-020, 0709.90-000, and 0709.52-000).

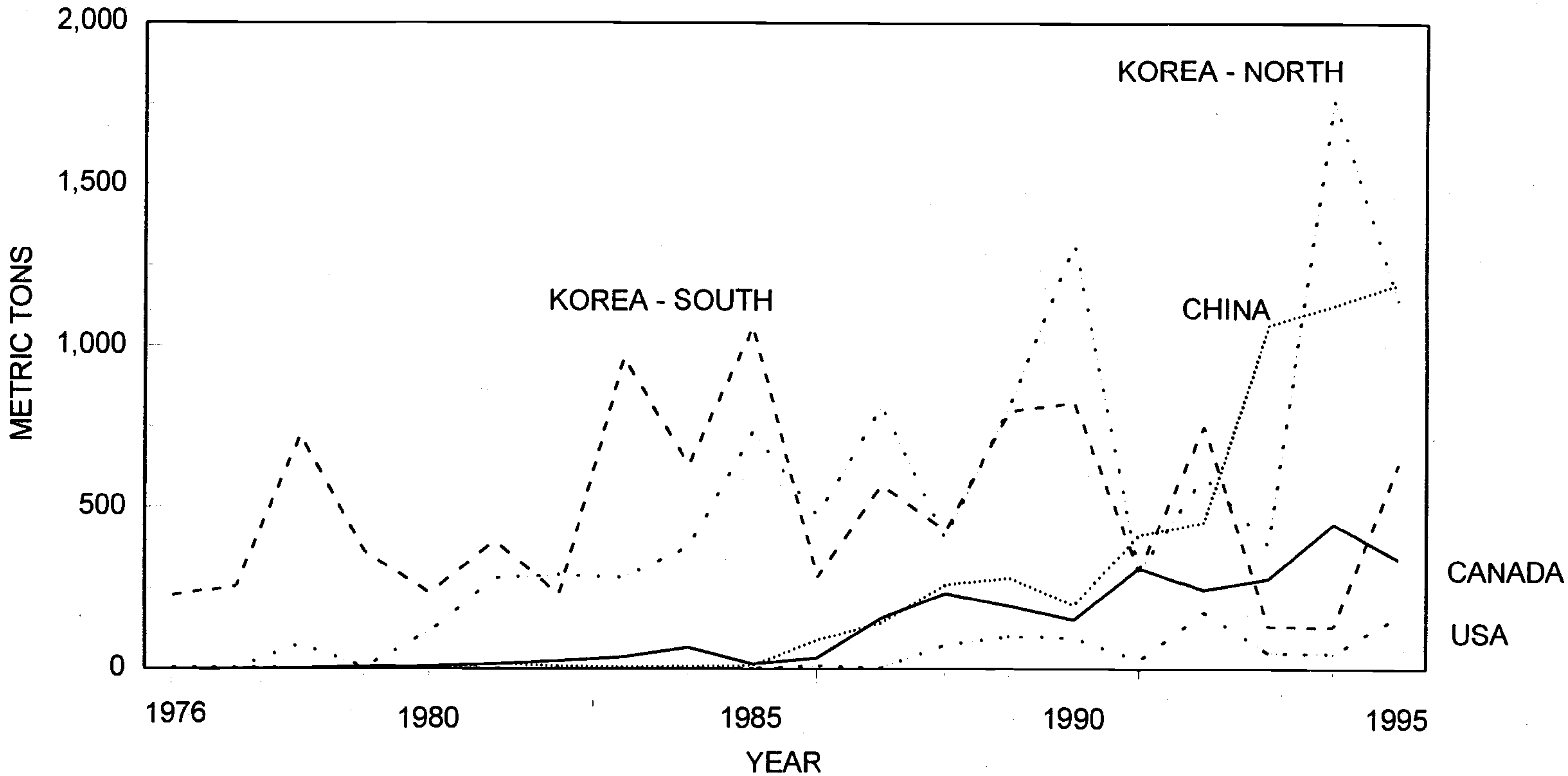
Increased availability of supplies of *T. matsutake* elsewhere in East Asia and market acceptance of related species, principally *T. magnivelare* in North America and *T. caligatum* from North Africa, have propelled the trend in increased pine mushrooms imports. Figure 2.2. shows the trend in import quantities from the five leading producer countries for pine mushrooms. A three-tiered market has developed where domestically produced pine mushrooms command the highest prices in Japan, imports from South Korea average one-half to one-third of the market price of domestic production, and imports of all species from all other countries average one-third to half of the value of South Korean imports (data from Japan Ministry of Agriculture, Forestry, and Fisheries, Japan Tariff Association, 1986-1995, and Redhead 1996 ms. draft).

Entry into the Japanese market by supplier countries has proceeded rapidly. Once supplies become reliably available from producer countries, rapid growth in pine mushroom imports follows. Strong surges in production came in 1981 from North Korea, 1986-87 from Canada and China, and in 1991 from the United States. Mexico and Morocco are examples of countries that since the mid-1980s have become consistent minor exporters. Much of the recent growth in pine mushroom imports from China and North Korea may in fact originate in the Russian Far East. Direct export from Russia, however, has not yet occurred. Other countries regularly exporting more than one metric ton of pine mushrooms annually to Japan since 1990 include Algeria, Bhutan, and Turkey.

2.3. Economic Use of *Tricholoma magnivelare*

Consumption of pine mushrooms in North America is poorly chronicled. Turner et al. (1987) document gathering and consumption of *T. magnivelare* along with *T. populinum* by the Interior Salish peoples of British Columbia and Washington, and Richards and Creasy (1996) report traditional collection by Karuk people in the Klamath region of

Figure 2.2. Pine mushroom imports to Japan from major producer countries, 1976-1995.



Source: Japan Tariff Association

southern Oregon and northern California. Japanese-American families in the Pacific Northwest have traditionally collected the species for personal use from favored sites (Zeller and Togashi 1934, Kinugawa and Goto 1978, Schlosser and Blatner 1995) near urban areas. Domestic United States consumption of the pine mushroom crop from Oregon, Washington, and Idaho accounted for less than 9% of the total in 1992 (Schlosser and Blatner 1995). A small amount of North American pine mushrooms is also exported to South Korea (Keith Blatner, 1996, personal communication). The remainder is destined for Japanese consumers. In some years, the Pacific Northwest share of the Japanese pine mushroom market has exceeded 20% but has averaged 16% for the period 1991-1995.

Mexican exports of *T. magnivelare* have developed since 1986. The commercial range of North American pine mushrooms (known as "hongo blanco de ocote") in Mexico ranges across the central tier of states from Michoacan to Veracruz. Harvests are, for the most part, temporally distinct from harvests in the Pacific Northwest pine mushroom zone. Pine mushrooms in Mexico are harvested during the rainy season from July to October (Villarreal and Perez-Moreno 1989, Japan Tariff Association data) and are the earliest stocks of *T. magnivelare* to reach the Japanese market each year. The Mexican share of Japanese consumption of imported pine mushrooms has amounted to 1% or less in the period 1991-1995 (Japan Tariff Association data). At present, wild mushroom brokers from the United States and Canada do not participate in the Mexican market (Villarreal and Perez-Moreno 1989 and 1995 Banco de México export trade statistics), and the Pacific Northwest and Mexican supply areas are best considered separately.

For the present analysis, I consider a combined Canada/United States supply source from the Pacific Northwest. Firms in the Pacific Northwest commonly purchase pine mushrooms from sources across the Canada-United States border (Meyer Resources, Inc, 1995) for eventual export to Japan. In their survey of firms purchasing edible wild mushrooms, Schlosser and Blatner (1995) found that 21% of processed pine mushrooms from the American Pacific Northwest are exported first to Canada and that 12% of the pine mushroom harvest from Oregon, Washington, and Idaho was processed outside the region. The authors attribute the diversion of the American harvest to Canadian domestic markets for pine mushrooms, particularly in British Columbia, and to the considerable number of processors and brokers located in western Canada. Trade data for edible wild mushrooms from both countries do not detect these cross-border transactions (Statistics Canada data for 1988-1995 and the United States Department of Commerce data for 1989-1995 under the harmonized trade product category no. 0709.51 for edible wild mushrooms). Actual country of origin for pine mushrooms from the Pacific Northwest is impossible to determine from currently available export trade data to Japan.

Exports of pine mushrooms to Japan drive intense commercial activity in the late summer and autumn in the Pacific Northwest. Schlosser and Blatner (1995) estimate the value paid to harvesters for pine mushroom harvests in the American Pacific Northwest to be US$7,941,815 (1990 U.S. dollars) in 1992 for 374 metric tons of product. The average annual price paid to pine mushroom harvesters for 1992 was US$18.46 kg^{-1} (1990 U.S. dollars). Among wild edible mushroom species harvested in the American Pacific Northwest, pine mushrooms ranked third after morels (*Morchella* spp.) and chanterelles (*Cantharellus* spp.) in volume harvested and ranked first in total harvest value. The 1992 pine mushroom harvest was nearly 2.5 times more valuable than the combined harvests of all other wild edible mushrooms.

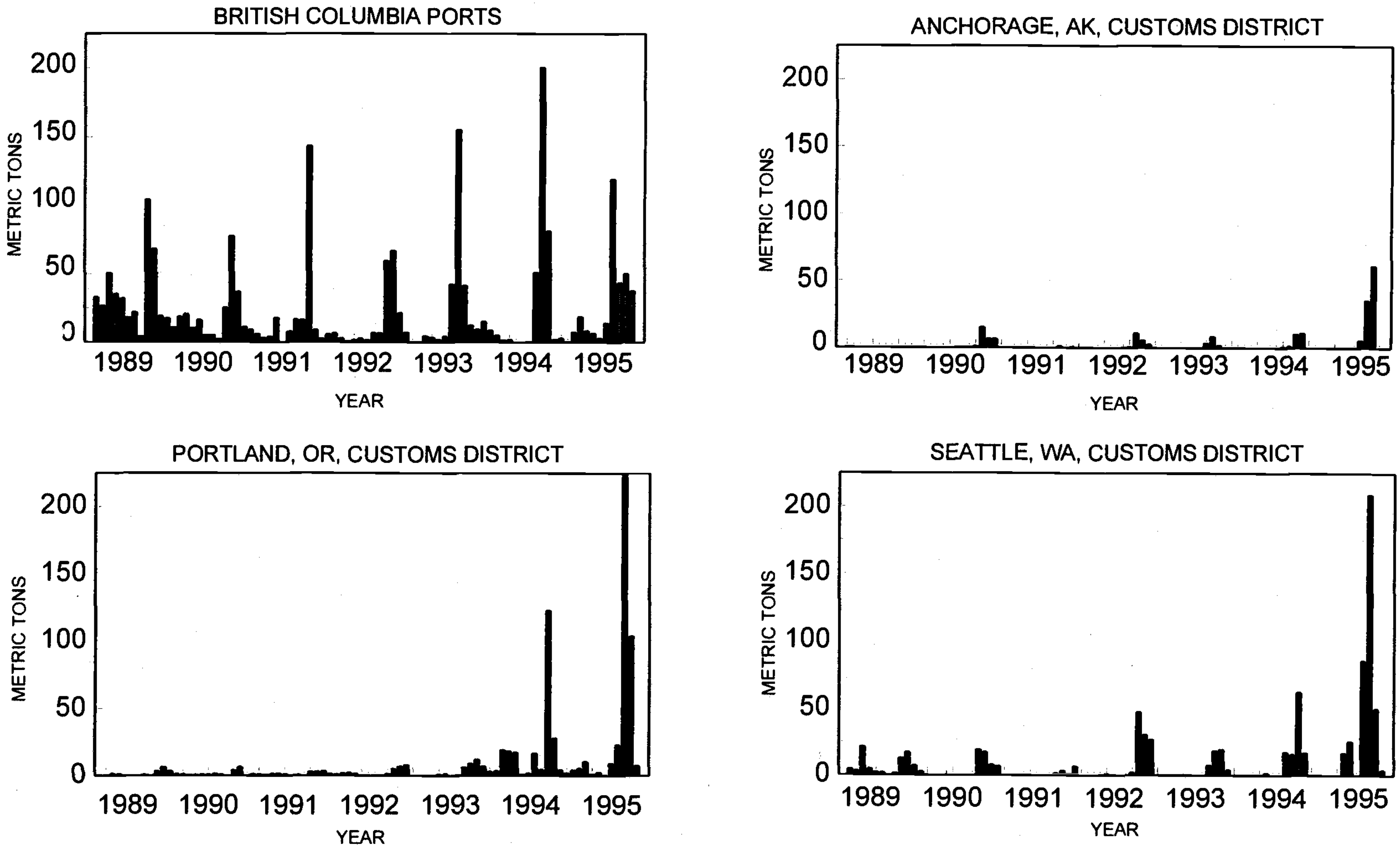
Under the international system of harmonized codes for categories of foreign trade products, export statistics from the United States and Canada do not distinguish among major commercial species as is done in Japan. Exports of pine mushrooms are not distinguishable from other species with existing data sets for exports from the two countries, except by inference. The seasonal pulse of pine mushroom harvests on the quantity and value of all pooled edible mushroom exports (code no. 0709.51-000) to Japan clearly appears in export data from Pacific Northwest ports in both countries to

Japan. The value and volume of edible mushroom exports rise markedly in most Septembers and continue to be high until December or January of the next year. Data from the Portland, Seattle, and Anchorage Customs Districts and from British Columbia ports demonstrate the seasonal jump in total volume and value of mushroom exports to Japan (figures 2.3. and 2.4.). Autumn peaks of wild edible mushroom exports to Japan, characteristic of the Pacific Northwest, do not appear in comparable data on mushroom exports to Japan from other customs districts in the United States or ports in Canada.

Expressed in constant 1990 US dollars, the price of *T. magnivelare* exports inferred from Canada and United States customs data rose steadily until 1993. Since then, the price of North American pine mushrooms has fallen slightly. Several reasons for the decline in prices are possible: (1) overall poorer quality of the pine mushroom harvests from North America; (2) increasing price competitiveness of pine mushrooms imported from China and North Korea; (3) increasing competitiveness of Oregon- and Washington-based firms seeking to take market share away from British Columbia exporters; and (4) a decline in real prices for luxury food items brought on by the 1992-1995 recession in Japan.

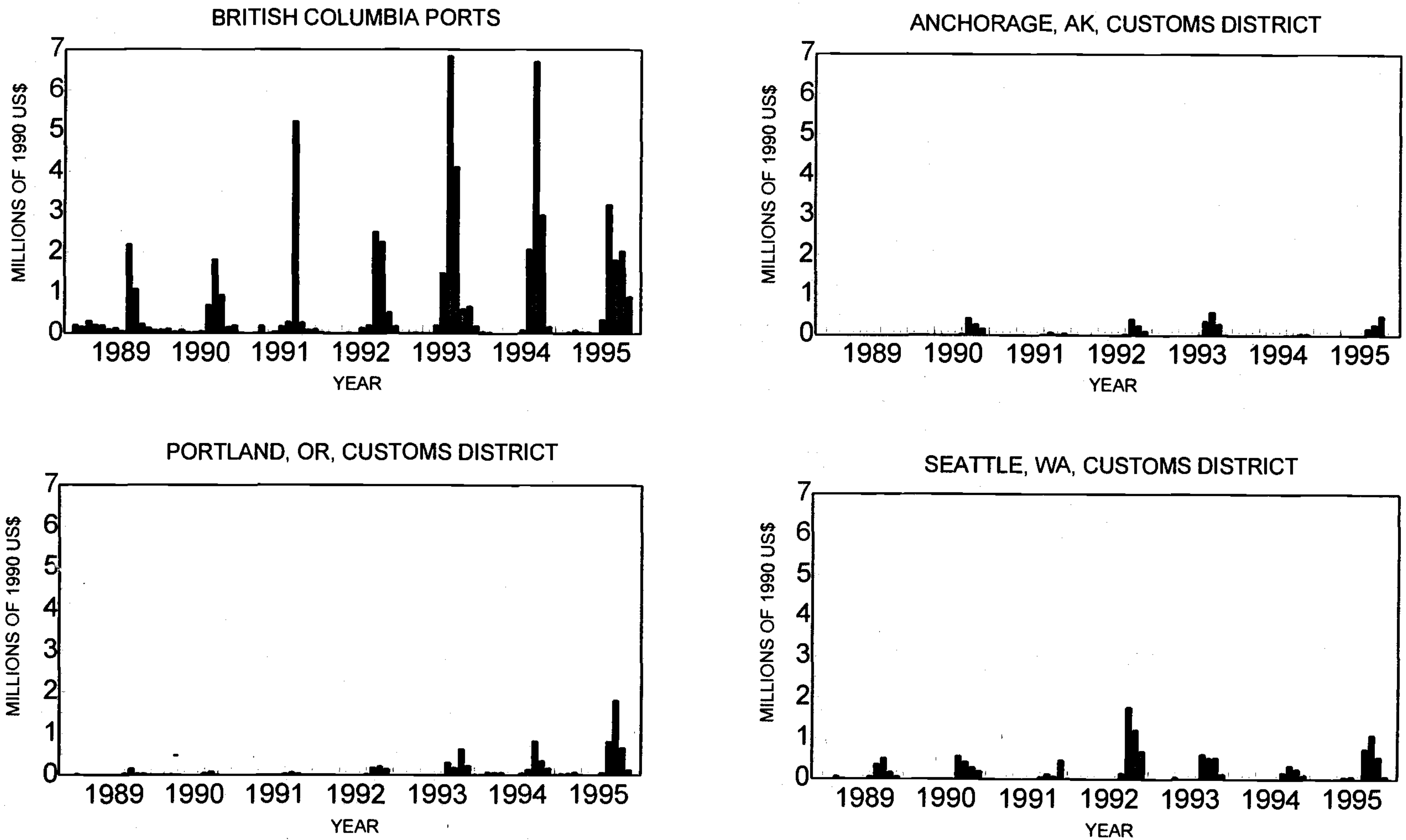
The only set of time-series data specifically documenting subregional production of *T. magnivelare* is for the period 1989-1992 collected by the Washington State Department of Agriculture (table 2.2.) under the Wild Mushroom Harvesting Act of 1988. The data are best considered provisional. Methods of data reporting differed among years and all reporting was voluntary. Data also differ considerably from trade data on exports in edible mushrooms to Japan recorded by the Seattle Customs District. The Washington State data is significant, however, because the data indicate wide swings in harvest amounts, reflecting actual year-to-year differences in weather patterns affecting the phenology and production of *T. magnivelare* basidiocarps.

Figure 2.3. Volume of edible mushroom exports to Japan from the Pacific Northwest by month, 1989-1995.



Sources: Statistics Canada, U.S. Department of Commerce

Figure 2.4. Value of edible mushroom exports to Japan from the Pacific Northwest by month, 1989-1995.



Sources: Bank of Canada, Office of the President, Statistics Canada, U.S. Department of Commerce

Table 2.2. Reported sales of North American pine mushrooms in Washington State, USA, 1989-1992.

Year	Commercial harvest (kg)	Average price ($ per kg)	% of total wild mushroom harvest volume	% of total wild mushroom harvest value
1989	1 179	29.77	1.01	5.38
1990	48 230	12.50	21.55	47.11
1991	454	23.72	0.46	1.23
1992	34 030	36.61	23.61	65.16

Source: Washington State Department of Agriculture, Wild Mushroom Harvesting in Washington State, annual reports 1989-1992. All prices are expressed in 1990 U.S. dollars .

2.4. Modeling the Market for Pine Mushrooms from the Pacific Northwest, 1976-1995

An econometric model to characterize Japanese market for pine mushrooms from the Pacific Northwest for the period 1976-1995 follows the model of Brooks et al. (1995) for timber products. Independent variables originally considered were real product price, per capita income, a time index in years, and Japanese import quantities of pine mushrooms lagged by one year. Data from the Japan Ministry of Agriculture, Fisheries, and Forestry for prices of domestically produced pine mushrooms are available only for the period 1985-1995. Annual per capita income is calculated as the quotient of the Japan gross domestic product in a given year (indexed to 1990 yen) and annual population figures (International Monetary Fund 1996).

Simplifying assumptions underlie the model. Pine mushrooms are sorted by six market grades by Pacific Northwest suppliers, depending on the size and maturity of the product. Japan Tariff Association trade data lump all market grades for all species under a single pine mushroom (matsutake) category. Therefore, percentages of composition by product grade must be assumed to remain constant from one year to the next and to not affect average annual prices and aggregate value.

Variables for a time index and for lagged consumption were dropped from the econometric model because they did not contribute significantly to the explanatory power of the model. Lagged consumption most likely is not significant because availability of pine mushrooms varies considerably from one year to the next as a function of weather. Data from South Korea suggest that no correlation exists among pine mushroom harvests from year to year (Cho and Lee 1995, Kang et al. 1989, Park et al. 1995).

Sources for estimating income were gross domestic product figures from the Bank of Japan, exchange rates from the International Monetary Fund, and import data from the Japan Tariff Association (see table 2.3.). The resulting simplified equation for demand in Japan for imported Pacific Northwest pine mushrooms follows the form:

$$\ln Q^{M}_{D} = -34.053 - 2.9368 * \ln \text{Price}_{NA} + 7.8684 * \ln \text{Income}_{Japan} + \epsilon \qquad (1)$$

where Q^{M}_{D} = National demand for imported pine mushrooms, in metric tons, from the Pacific Northwest;

Price_{NA} = average wholesale price in constant 1990 ¥ per metric ton for pine mushrooms exported from the Pacific Northwest to Japan;

Income_{Japan} = Japan per capita income, based on gross domestic product in billions of constant 1990 ¥ divided by millions of people; and

ϵ = a random error term.

All coefficients are significant at $p < .01$, the adjusted r^2 for the equation is .88, and first order autocorrelation is not significant at $\alpha = .05$ (Durbin-Watson statistic 1.3965, n=20 years, 1976-1995).

The coefficient of the price variables being less than -1.0 would indicate an elastic demand for pine mushroom from both Asian and North American sources. Changes in

Table 2.3. Annual data for Japanese domestic production and imports of pine mushrooms, 1976-1995.

	JAPAN		ALL IMPORTS			PACIFIC NORTHWEST				SOUTH KOREA			NORTH KOREA		
	PROD	¥ PRICE	PROD	¥ VALUE	¥ PRICE	PROD	¥ VALUE	¥ PRICE	US$ PRICE	VOLUME	¥ VALUE	¥ PRICE	VOLUME	¥ VALUE	¥ PRICE
1976	604	NA	232	1.512	7 374	0*	0.000*	5 759	25.29	228	1.476	7 329	4	0.035	9 899
1977	428	NA	259	2.351	10 076	2	0.007	3 565	17.45	254	2.328	10 175	3	0.017	6 228
1978	620	NA	803	4.603	6 530	5	0.014	2 969	16.05	721	4.298	6 787	76	0.291	4 359
1979	658	NA	377	3.519	9 917	9	0.042	5 129	24.95	360	3.454	10 171	6	0.015	2 817
1980	457	NA	362	2.999	7 479	10	0.036	3 320	17.57	234	2.623	10 107	115	0.328	2 561
1981	208	NA	704	4.888	6 173	17	0.100	5 163	28.66	393	3.872	8 750	280	0.852	2 707
1982	484	NA	551	4.110	6 511	25	0.146	5 126	26.65	229	2.525	9 616	288	1.383	4 195
1983	742	NA	1 288	7.785	5 402	38	0.201	4 674	24.46	961	6.637	6 173	282	0.918	2 903
1984	180	NA	1 082	7.348	6 084	69	0.400	5 204	26.42	629	5.644	8 034	375	1.270	3 032
1985	820	15 076	1 817	10.297	5 132	18	0.126	6 186	34.17	1 058	7.646	6 546	730	2.477	3 073
1986	199	31 617	980	8.347	8 489	42	0.254	6 012	43.46	282	4.979	17 619	473	1.873	3 949
1987	464	22 761	1 712	10.125	6 128	161	0.727	4 679	36.72	569	5.779	10 526	814	2.731	3 476
1988	406	23 390	1 430	10.941	8 006	307	1.375	4 687	37.26	427	6.391	15 668	402	1.646	4 282
1989	457	28 202	2 210	14.431	6 664	293	1.040	3 617	26.11	797	8.460	10 832	813	3.331	4 180
1990	513	24 133	2 661	15.881	5 969	247	1.128	4 571	31.52	823	7.733	9 395	1 318	5.493	4 168
1991	267	32 135	1 435	14.905	10 446	340	1.808	5 358	42.42	305	7.698	25 427	301	2.580	8 613
1992	187	49 558	2 244	18.487	8 424	419	2.120	5 176	42.97	749	10.511	14 350	597	2.762	4 733
1993	349	43 128	1 943	12.643	6 849	329	2.331	7 459	66.56	131	2.321	18 626	383	2.292	6 301
1994	120	24 425	3 622	17.933	5 318	494	2.144	4 658	45.07	139	2.653	20 497	1 761	6.928	4 226
1995	211	7 004	3 515	18.566	5 729	503	2.288	4 932	51.74	633	6.719	11 513	1 141	4.074	3 872

¥ VALUE is expressed as millions of 1990 ¥, ¥ PRICE is expressed as 1990 ¥ per kilogram.

US$ PRICE is expressed in 1990 US$ per kilogram.

NA - data are not available *amount is less than 0.5 metric ton and is valued at less than 1 million 1990 ¥

pine mushroom prices give rise then to proportionately larger changes in Japanese consumption in the opposite direction. Definitive conclusions are not possible without data for prices for Japanese production or suitable surrogate data.

2.5. Scenarios for Future Price Trends

Price forecasts for the next 25 years based on the historic performance of pine mushroom prices in the past twenty years can test the feasibility of directing forestry investment to increasing production of pine mushrooms in Pacific Northwest ecosystems where they are commercially produced now and even to expanding the land base of commercial production to sites where commercial production does not normally occur. Scenario analysis can help interested landowners determine risk and robustness of decisions under uncertainty. This task becomes crucial for skeptical North American investors unaccustomed to the notion of mycoforestry.

Recasting the regression between price and quantity in (1) such that price is the dependent variable can form a basis for examining how pine mushroom prices might fare in the future. Average annual prices of pine mushrooms from 1976-1995, expressed in constant 1990 U.S. dollars, are correlated best with per capita income in Japan expressed in constant 1990 yen:

$$Price_{NA} = \exp(-34.058 - \ln(Q^{M}{}_{A}) * \ln(Income_{Japan})/2.9368) * 10, \quad (2)$$

where variables are defined as in (1) and ten is the multiplier to get the unit price in yen per kilogram. Quantity demanded in equation (1) is assumed to be in equilibrium with quantity supplied and substitutes here for the Pacific Northwest market supply of pine mushrooms.

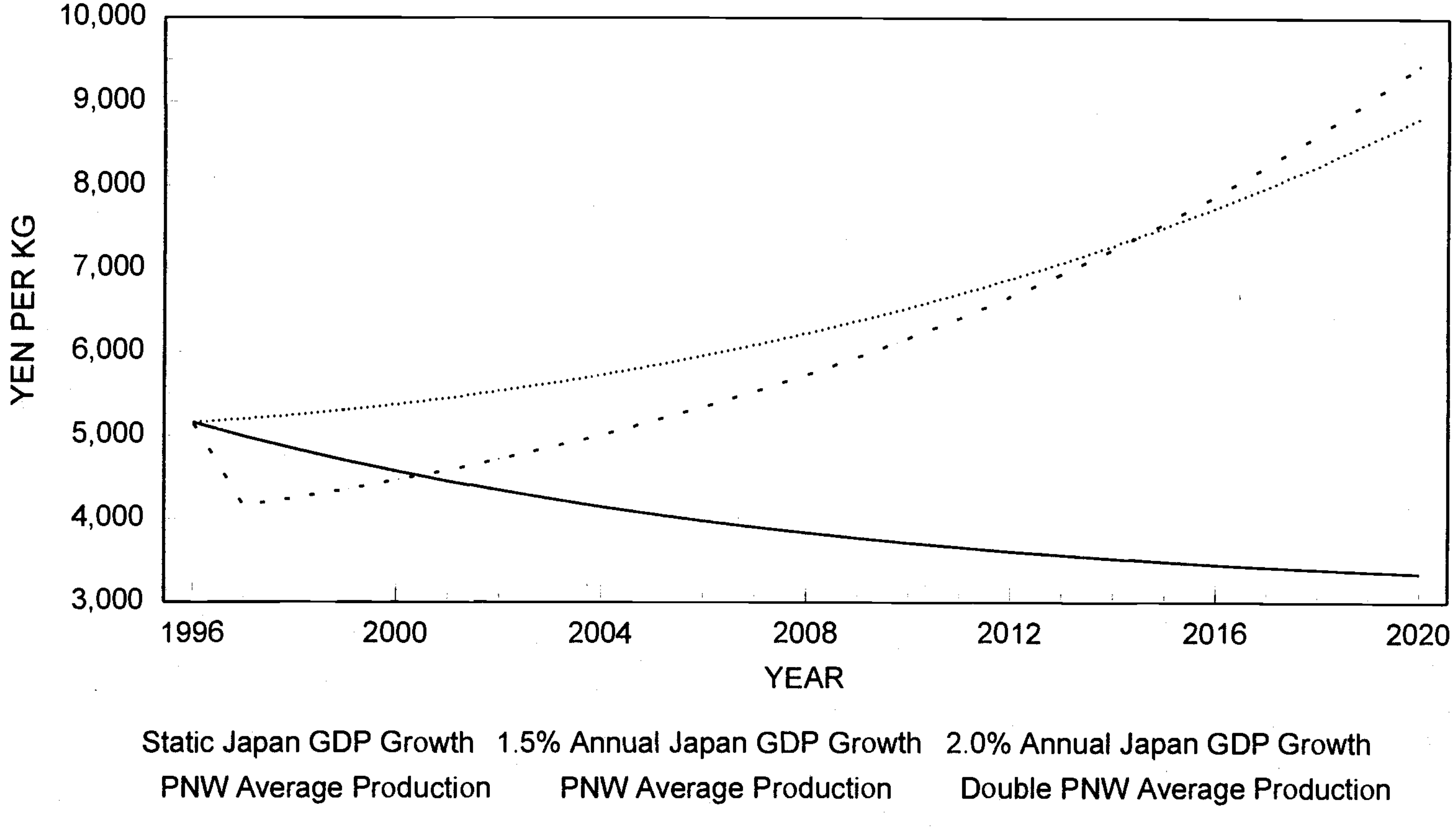
Figure 2.5. illustrates a range of possible scenarios that test robustness of uncertain investments under different assumptions. The first scenario is a pessimistic future, with a static Japanese gross domestic product (GDP); it also assumes the North American pine mushrooms continue to be produced at the same rate seen between 1986 and 1995. A second scenario also assumes that North American production remains at 1986-1995 levels, and economic growth is modest, reflecting the average rate of GDP (1.5% annual growth) in Japan for the period 1992-1995, a period of recession (Japan Government Planning Agency 1996). Doubling the historic average production of pine mushrooms in North America and assuming 2.0% annual economic growth provides a contrasting outlook. Prices are depressed at the start as production immediately doubles, but by 2015 prices exceed the scenario with static North American production and Japan GDP growth at 1.5%. In all scenarios, population growth is modeled identically as growing at an exponentially declining rate, reflecting population growth rates in Japan during the period 1976-1995:

$$\text{Rate}_{\text{population growth}} = 1.0112 - 0.0028177 * \ln \text{Year}_n \; , \qquad (3)$$

where $\ln \text{Year}_n$ is the nth year since 1975 (coefficients significant at $p < .01$, adjusted $r^2 = .95$, and the Durbin-Watson statistic, adjusted for autocorrelation, = 1.7789).
The population increase explains the decline in per capita income under the assumption of static GDP in Japan in scenario one.

Another factor not modeled directly here is the role of currency exchange rates. Perceptions of high prices expressed in United States and Canadian dollars for pine mushrooms is the result of North American currency devalued against the yen. The trend toward climbing yen value, evident since the mid-1970s, may not continue indefinitely, and an examination of the role of currency rates on luxury food commodities is important to understanding changes in pine mushroom consumption. Continued modest economic growth in Japan would increase discretionary income for specialty foods even more. Reduced economic growth may mean that sources of less expensive pine mushrooms,

Figure 2.5. Future price scenarios for pine mushrooms in the Pacific Northwest, 1996-2020.



All prices are expressed in 1990 Japanese yen.

such as those from the Pacific Northwest and North Korea, might eventually become substitutes in a more competitive market.

2.6. Discussion

Japanese imports of pine mushrooms have expanded unabated in the last twenty years. There is little reason to expect the market in Japan to decline, barring an enduring economic drop-off in Japan or a technological change involving industrialization of pine mushroom production of the kind developed for non-mycorrhizal species such as shiitake. Expanding economic production of *T. magnivelare* in Pacific Northwest forests presents an opportunity to diversify regional forest production. Potential yields have yet to be estimated regionally. Technology and successful models of technological application already exist, however. Forest policy and practices in South Korea provide an example of efficient production in forest ecosystems of high-quality pine mushrooms for export. Despite the constraints of a comparatively small forest land base that must also meet other needs of 46 million people, attention to cultivating pine mushrooms in South Korea has paid off. Pine mushroom production contributes substantially to national income from forest products income in South Korea, comprising 4.34% of the total in South Korea for 1989 (Sung and Kim 1991).

Annual export production in South Korea in the best years has exceeded one thousand metric tons (Japan Tariff Association data for 1985) although exports may amount to as little as one-tenth of capacity in years of unfavorable environmental conditions for fruiting (e.g. 1993-94). Variable annual production can pose unacceptable risk for some landowners and must be considered in a financial analysis. Also, it is important to consider the economic value of current and potential production of *T. magnivelare* in perspective with other forest products from the Pacific Northwest. For example, the value of Douglas-fir logs exported to Japan from Washington and Oregon in 1995 amounted to $908.9 million as compared to approximately $5.9 million (both in constant 1990 U.S. dollars) for pine mushrooms from the same states (Warren 1996 and US Department of Commerce 1995 data for wild edible mushrooms from the Seattle and Portland Customs Districts).

Despite a far larger land base of likely forest habitats available for culturing *T. magnivelare*, Pacific Northwest forest management for pine mushroom production is underdeveloped in contrast to South Korea. Export quantities from the American Pacific Northwest exceeded 500 metric tons for the first time in 1995. Increased investment in pine mushrooms in suitable habitats may substantially increase net value to stands with otherwise marginal timber value. Lodgepole pine (*Pinus contorta*) stands, both at coastal and high-elevation sites in the Cascade Range of Pacific Northwest, are likely candidate forest types, for example (Pilz et al. 1996a,b).

Land tenure is an important factor in large-scale pine mushroom production. In South Korea, the major portion of pine mushroom production comes from privately-owned forests (Sung and Kim 1991). Where rights to access for managing and harvesting pine mushrooms are clearly defined and secure, there is greater incentive to invest in pine mushroom management. Currently, on public lands in the American Pacific Northwest, pine mushroom harvesting occurs under conditions of essentially open access. Some National Forest jurisdictions charge a nominal fee, but the fee is ineffective in controlling the density of pickers and in raising funds for long-term conservation management of pine mushrooms. Evidence of the need for improved management of pine mushroom resources and of the need for new institutional arrangements to govern access to the resource appears in accounts of social conflict resulting from competition among pickers during the pine mushroom harvest season (e.g., Lipske 1994 and Richards and Creasy 1996). Increasing the supply of pine mushrooms through more intensive management may improve access to the resource, reduce social stress, and augment income for landowners and harvesters. New institutional arrangements are needed as well to counter possible incentives for increased illegal pine mushroom collecting in the event of larger crops and to ensure that benefits reach intended agencies, forest management programs, and people.

Funding for developing joint production systems based on agroforestry models may be particularly useful for resolving conflict in objectives of timber management and pine mushroom management. Agroforestry systems involving timber and understory fungi are not yet in place in the Pacific Northwest, but systems incorporating *T. magnivelare* have already been proposed for implementation in central Mexico (Villarreal 1993). Novel means of forest management to increase joint production of timber and pine mushrooms or to increase total net value of stands managed for both resources have yet to be devised in the Pacific Northwest.

Following is a summary list of tasks for instituting a program of intensified pine mushroom production in the Pacific Northwest:

- determine forest types best suited to commercial production of pine mushrooms;
- investigate the physiological and environmental factors limiting pine mushroom productivity and consequences to other resources, including fungal species diversity, from intensified management for commercial production;
- design vegetation management for agroforestry systems that increases net productivity and value in forest stands producing pine mushrooms;
- test management practices proposed for increasing pine mushroom productivity;
- establish networks and opportunities for information exchange among forest managers and forest researchers in East Asia, the Mediterranean Basin, and North America regarding innovative management and processing for pine mushrooms;
- undertake market research to set the groundwork for expanding East Asian markets and domestic North American consumption of North American pine mushrooms;
- characterize effects of seasonality on prices for pine mushrooms; and

- establish socially-acceptable arrangement for harvesting pine mushroom, particularly on public forest lands, that support management objectives and benefit harvesters and continuing productivity of pine mushroom populations.

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3. Composition, Volume, and Prices for Major Softwood Lumber Types in Western Oregon and Washington, 1971-2020

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Abstract

An analysis of lumber prices provided regressions for price trends during the period 1971-1995 for composite lumber grades of major species in the Pacific Northwest west of the Cascade Crest. The analysis includes coastal Douglas-fir and hem-fir lumber, coastal and inland Pacific Northwest ponderosa, sugar, and western white pines, and inland Pacific Northwest and Rocky Mountain lodgepole pine. Future prices of grades by species group are based on these price trends and the latest average regional lumber values established in the Timber Assessment Market Model (TAMM). Land managers can use the price projections in financial analyses of management practices that are designed to affect the quality of timber resources.

Keywords: Douglas-fir, hem-fir, lodgepole pine, lumber prices, ponderosa pine, price trends, sugar pine, Timber Analysis Market Model, western white pine, whitewoods.

3.1. Introduction

Land managers provide multiple outputs of goods from public forests. Suitable management satisfies criteria for both the quantity and quality of production. Increasingly, criteria for production must also satisfy societal goals for biological diversity, conservation of biological processes, recreation and clean air and water. Interest in longer timber rotations and for uneven-aged stand management is growing (Curtis 1995, Halpern and Spies 1995, Weigand and others 1994). The call for more complex forest management with multiple goals necessitates site-specific vegetation management. Management of timber resources in the Pacific Northwest now involves more tree species, more ecosystem types, and more products and services than ever before.

Commercial reforestation in the Pacific Northwest has traditionally concentrated on Douglas-fir, western hemlock, and ponderosa pine. As forest landscape management broadens to consider concerns of biological diversity and economic diversification based on multiple species, timber species that have not been intensively managed until now are receiving more attention. In the Pacific Northwest west of the Cascade Crest, these species may be uncommon or local in distribution, such as sugar pine (*Pinus lambertiana* Dougl.) and western white pine (*P. monticola* Dougl. ex D. Don), or higher-elevation species such as mountain hemlock (*Tsuga mertensiana* (Bong.) Carr.), noble fir (*Abies procera* Rehd.), Pacific silver fir (*Abies amabilis* Dougl. ex Forbes), and lodgepole pine (*P. contorta* Dougl. ex Loud. var. *murryana*). Reasons for their silvicultural neglect have been unfamiliarity with species and site conditions (Halverson and Emmingham 1982), problems with disease and pathogens (Snellgrove and Cahill 1980), and preferred use of timber resources with better quality or easier access. Timber production with lodgepole pine, for example, in the Rocky Mountains (Cole and Koch 1995, Koch 1996) and in Europe (Fitzsimmons 1989) demonstrates the economic prospects for lodgepole pine in the Pacific Northwest. In addition, attention to a larger suite of tree species under management also supports, in part, the goals of increased biological diversity in managed forests.

A shift in the quality of lumber production and a shift toward stand compositions that replicate natural species diversity has coincided with the phase-out of old-growth timber harvests in the Pacific Northwest. In Federal public forests, the timber supply over the long-term may be quite different from production in the recent past. One important objective of the President's Northwest Forest Plan (Jacobs 1994) is creation and maintenance of managed forest stands that conserve endangered species. Timber with small diameter or with variable size and quality will be available from thinnings in stands managed for eventual recreation of old-growth or late-seral features. Also, particularly for late thinnings in long rotations or for cyclic cuttings in uneven-aged stands, timber may be harvested that produces high-quality lumber products, of the kind that has become rare over the last 25 years. The future timber supply for producing lumber from Federal lands in the Pacific Northwest may differ considerably from the timber supply from private industrial forest lands as well.

Forest managers need to know what are the likely product premiums for lumber from future timber produced in managed forests of the Pacific Northwest. Several tools already exist to estimate the costs of management for improved timber and lumber quality. Models to predict premiums for pruned wood already exist (Bolon and others 1992, Fight and others 1987), for example. The present analysis provides information about lumber prices that is useful in decisions about stand management in the region. This study updates and expands work by Adams and others (1988) and Haynes and Fight (1992) for western Oregon and Washington. An overview first summarizes general and species-specific trends in the amount, quality, and value of lumber production in the Pacific Northwest from 1971 to 1995. Regression equations based on existing data relate lumber prices for specific grade categories to average prices for regional lumber production. The regressions are extrapolated to the year 2020 to give a scenario of future prices of lumber grades for six major species or species groups in western Washington and Oregon. A discussion of the implications of future price trends on production and value of timber resources on Federal public land in the Pacific Northwest concludes the study.

3.2. Data Sources

The database for this study consists of records for lumber quantities sold and average lumber prices both in aggregate and by individual tree species and grade. Data are from year-end issues of the Coast F.O.B. Price Summary and the Inland F.O.B. Price Summary published by the Western Wood Products Association (hereafter WWPA), Portland, OR, for the period 1971-1995. Sample data published for lumber prices in WWPA reports account for 65 to 70 percent of annual regional lumber production. WWPA summaries provide nominal prices (unadjusted for inflation) for actual transactions for lumber production.

Table 3.1. gives average annual prices, expressed in 1990 U.S. dollars, of lumber in aggregate produced in mills from the Pacific Northwest. Constant dollars remove effects of inflation to allow comparison of real prices over time. Average lumber prices for the region west of the Cascade Crest ("west side") come directly from WWPA reports. Estimates of prices for the Pacific Northwest east of the Cascade Crest ("east side") are derived using the method of Adams and others (1988). The east-side figures are a lumber price index consisting of inland West production of ponderosa pine, Douglas-fir, western larch, and hem-fir lumber, weighted by volume.

For lumber grade categories of Douglas-fir, hem-fir, and ponderosa pine, definitions follow the system established in Haynes and Fight (1992). New lumber grade categories are established in this study for sugar pine, western white pine, and whitewood (including

Table 3.1. Average real lumber prices in the Pacific Northwest, 1971-1995.

Year	Westside[a]	Eastside[b]
	1990 U. S. dollars per thousand Scribner board feet	
1971	351.11	369.77
1972	395.93	429.81
1973	497.45	542.45
1974	384.09	420.58
1975	317.41	347.72
1976	371.79	426.42
1977	401.65	462.89
1978	425.23	530.45
1979	434.10	499.96
1980	346.68	384.10
1981	276.41	353.29
1982	229.78	298.22
1983	260.67	369.87
1984	238.88	342.85
1985	237.38	337.36
1986	246.83	303.82
1987	261.28	366.07
1988	271.37	349.78
1989	286.74	347.07
1990	262.90	312.29
1991	258.20	333.58
1992	295.87	395.55
1993	398.97	503.54
1994	386.27	485.70
1995	333.81	410.32

[a] Average value is based on the WWPA total average annual value of all lumber of all species milled in western Oregon and Washington.

[b] Average value is based on the WWPAtotal average annual value of all ponderosa pine, hem-fir, and Douglas-fir/western larch lumber produced in the Inland U.S. West (Adams and others 1988).

lodgepole pine) lumber. Prices and product proportions for individual lumber grade categories used in this study are volume-weighted averages of prices for composite lumber grades. Appendix 3A provides details of grade composition of lumber grade categories combined into the composite grades for the four species and two species groups.

Nominal prices and proportions for the lumber grade categories of Douglas-fir, hem-fir, and ponderosa pine, for the years 1971-1990, are taken from Haynes and Fight (1992) and, for the years 1991-1995, from Warren (1996). These sources originally derived their data from the WWPA sources. Nominal prices and proportions for the new timber species groups are also synthesized from the WWPA publications. Nominal prices by species group and lumber grade category are listed in tables 3.2. through 3.7. Information about weighted proportions of lumber grade categories to total regional lumber production are found in tables 3.8. to 3.13. Real prices in 1990 U.S. dollars are calculated from nominal prices using the producer price index for total industrial commodities (Office of the President, 1996; see table 3.14.).

3.3. Trends in Lumber Prices and Production, 1971-1995

Five additional years of data (1991-1995) substantiate many of the trends in lumber prices observed by Haynes and Fight (1992). The annual average value of westside lumber has remained below the computed value of lumber produced in eastside mills for all years, 1971-1995 (table 3.1.). Average real lumber prices in both the west-side and east-side Pacific Northwest for the period 1971-1995 have also fluctuated cyclically. A decline in real lumber prices that began in the late 1970's ended in the late 1980's as court injunctions and plans to conserve endangered species restricted timber sales. Lumber prices during the past eight decades have increased at an annual rate 0.9 percent annually (Sohngen and Haynes 1994). Rising average prices for lumber since 1985 may represent

Table 3.2. Nominal prices for Douglas-fir lumber, Pacific Northwest coast mills, 1971-1995.

Year	C select	D select and shop	structural items	heavy framing	light framing	utility	economy
	------------------------U. S. *dollars per thousand Scribner board feet*						------------------------
1971	228	146	126	122	105	74	33
1972	280	164	143	141	126	93	41
1973	471	216	210	198	161	117	67
1974	474	238	238	184	141	82	47
1975	406	225	185	165	139	84	45
1976	486	276	229	217	174	110	49
1977	504	342	289	215	215	148	61
1978	593	406	325	395	235	170	86
1979	891	480	410	334	246	179	86
1980	929	506	365	271	207	150	85
1981	747	426	329	263	193	137	83
1982	648	375	283	198	159	126	78
1983	685	426	262	222	201	162	87
1984	688	407	249	223	189	137	72
1985	671	410	249	226	190	131	68
1986	726	405	240	229	191	132	67
1987	837	411	257	258	206	138	66
1988	927	474	297	285	219	138	85
1989	1078	503	325	330	246	168	110
1990	1236	521	305	310	232	156	102
1991	1200	535	316	306	230	158	101
1992	1350	576	348	349	273	205	123
1993	1197	809	511	517	393	295	175
1994	1413	752	478	485	385	294	148
1995	1172	699	448	442	330	224	142

Sources: Haynes and Fight (1992) and Warren (1996)

Table 3.3. Nominal prices for hem-fir lumber, Pacific Northwest coast mills, 1971-1995.

Year	C select	D select and shop	structural items	heavy framing	light framing	utility	economy
	U.S. dollars per thousand Scribner board feet						
1971	207	138	126	115	101	71	34
1972	241	151	148	138	122	90	41
1973	344	209	193	181	157	113	62
1974	440	233	179	179	140	81	44
1975	351	208	164	161	133	79	42
1976	427	258	201	206	164	106	48
1977	453	287	229	236	192	135	58
1978	587	345	259	256	222	164	85
1979	676	400	290	302	234	160	78
1980	718	405	257	245	195	132	78
1981	661	362	229	244	183	131	79
1982	712	319	202	209	158	123	70
1983	737	386	245	240	205	156	97
1984	683	348	227	228	187	128	79
1985	638	337	226	232	189	123	79
1986	606	343	242	248	197	129	75
1987	601	414	273	286	215	131	76
1988	633	461	273	289	221	137	89
1989	718	466	274	298	234	155	105
1990	820	500	270	283	224	150	97
1991	800	463	283	277	230	147	96
1992	883	488	321	312	266	188	129
1993	-	640	433	443	365	238	179
1994	-	596	436	452	384	268	164
1995	-	590	357	397	312	209	154

Sources: Haynes and Fight (1992) and Warren (1996)

Table 3.4. Nominal prices for ponderosa pine lumber, western U. S. mills, 1971-1995.

	4/4 selects and #1 shop					4/4 common and 8/4 standard 5/4 and thicker moulding and shops					4/4 commons and 8/4 standard and better				low value	
Year	C and better 6-12 in	D 12 in	C and btr. 4 in, D 6-10 in	D 4 in	#1 shop	Mldg. and better	#1 shop	#2 shop	#3 shop	shopout	2 com. 12 in	2com. 4-10 in	3 com., 6-12 in 8/4 dimen.	3 com., 4 in 4 com., 4-12 in	#3 and utility	5 com. and economy
	U. S. dollars per thousand Scribner board feet															
1971	384	307	262	197	136	301	220	158	133	85	134	113	93	75	73	38
1972	402	334	284	210	157	314	247	185	157	107	165	138	121	101	90	50
1973	479	410	369	285	207	392	294	232	195	159	242	207	164	144	116	78
1974	612	550	499	305	210	429	314	252	208	133	270	211	141	107	73	57
1975	646	546	454	257	173	477	278	206	153	97	246	188	125	88	73	47
1976	708	615	444	334	233	531	398	326	248	143	272	219	166	129	98	58
1977	816	725	514	360	280	549	454	384	286	173	331	272	196	146	123	72
1978	1001	906	671	489	349	934	526	462	331	206	373	329	232	184	144	98
1979	1398	1255	1004	532	333	955	554	481	304	210	441	359	263	184	145	96
1980	1187	865	610	401	330	813	549	473	308	203	450	289	237	165	122	87
1981	1110	965	608	467	333	817	589	509	355	218	385	278	245	164	127	89
1982	1187	865	610	401	330	813	549	473	308	203	450	289	237	165	122	87
1983	1214	1404	659	513	363	1056	662	570	401	225	388	305	222	160	155	90
1984	1363	1163	724	499	368	949	622	506	349	203	432	319	235	149	124	83
1985	1463	863	779	506	342	1087	614	498	366	204	456	312	208	143	127	75
1986	1509	1169	1021	654	636	1093	688	576	404	207	430	325	227	163	130	79

Table 3.4. continued.

1987	1563	1336	1088	703	442	1306	762	644	413	224	447	367	247	175	131	79
1988	1892	1510	1076	689	452	1282	746	625	411	229	505	363	246	174	137	87
1989	1805	1523	1016	740	438	1265	730	589	434	258	532	331	261	189	155	105
1990	1478	1453	996	683	435	1051	677	542	414	247	534	356	248	187	145	99
1991	1335	1259	911	654	425	1090	795	655	517	259	523	372	272	184	147	99
1992	1749	1484	1195	856	622	1371	970	845	631	335	686	423	337	226	196	133
1993	2198	1910	1510	1019	700	1957	1189	1059	741	447	706	498	381	289	250	174
1994	2347	2343	1316	880	800	1753	1145	1017	701	448	803	569	413	302	254	157
1995	1887	1982	1095	737	550	1491	1089	972	661	410	695	507	367	251	215	158

Sources: Haynes and Fight (1992) and Warren (1996)

Table 3.5. Nominal prices for sugar pine lumber, western U. S. mills, 1971-1995.

Year	4/4 selects and #1 shop				5/4 and thicker moulding and shops					4/4 commons and 8/4 standard and better				low value
	C and better 6-12 in	C and btr. 4 in, D 6-12 in	D 4 in	#1 shop	Mldg. and better	#1 shop	#2 shop	#3 shop	shopout	2 com. 12 in	2com. 4-10 in	3 com., 6-12 in 8/4 dimen.	3 com., 4in 4 com., 4-12 in #3 and utility	5 common economy
	U. S. dollars per thousand Scribner board feet													
1971	400	307	224	140	309	226	165	133	106	187	139	97	76	38
1972	432	347	248	163	329	255	193	156	123	215	165	123	99	48
1973	528	442	323	225	413	303	243	206	207	270	256	183	145	91
1974	651	568	346	212	444	331	260	227	215	289	286	159	105	67
1975	681	557	301	159	500	295	225	176	182	288	267	141	92	48
1976	746	551	421	231	546	403	337	265	209	371	294	189	132	61
1977	848	622	482	278	571	452	390	295	186	380	345	231	151	76
1978	1104	853	623	351	959	530	472	350	229	451	384	267	191	112
1979	1478	1202	729	327	950	557	486	319	233	435	464	314	195	116
1980	1389	1050	626	333	860	560	482	315	232	418	451	296	174	96
1981	1277	901	749	373	856	601	528	367	255	478	441	312	183	99
1982	1269	1001	769	293	924	477	381	267	224	452	421	264	137	85
1983	1293	1114	818	378	1038	673	590	406	236	488	436	257	170	103
1984	1390	993	681	351	954	605	498	355	220	466	421	264	149	90
1985	1481	889	616	333	1117	618	505	365	221	438	423	229	156	89
1986	1550	1067	801	368	1121	707	594	418	227	520	415	250	173	100

Table 3.5. continued.

1987	1722	1260	837	414	1338	794	655	425	247	607	437	264	185	96
1988	2031	1374	917	434	1306	782	636	412	248	604	476	262	172	98
1989	2005	1380	885	420	1294	745	583	423	276	603	491	279	190	119
1990	1681	1187	795	427	1112	674	529	401	268	607	499	287	181	122
1991	1566	1074	808	411	1159	796	673	538	275	579	511	305	174	111
1992	1812	1292	1030	611	1389	966	842	619	349	796	636	419	249	145
1993	2497	1734	1311	690	1907	1162	1038	715	417	885	675	444	305	185
1994	2384	1716	1273	777	1774	1135	1000	697	415	-	773	480	308	188
1995	2248	1498	1271	580	1435	1077	946	663	383	-	694	442	262	159

Sources: Western Wood Products Association. 1971-1995. Inland F.O.B. Price Summary.

Table 3.6. Nominal prices for western white pine lumber, western U. S. mills, 1971-1995.

Year	D select and better	shop and better	2 common	3 common	4 common	5 common
	U. S. dollars per thousand Scribner board feet					
1971	273	138	149	99	77	33
1972	310	164	187	134	102	45
1973	393	224	258	202	146	81
1974	519	249	327	198	120	66
1975	447	204	275	150	94	41
1976	508	273	317	210	133	56
1977	580	309	351	246	150	69
1978	756	419	467	297	185	96
1979	1080	395	479	329	192	110
1980	716	342	446	267	166	87
1981	767	374	480	278	163	85
1982	826	324	493	257	133	73
1983	864	415	495	261	153	80
1984	917	400	512	297	154	81
1985	949	401	576	287	137	75
1986	1151	487	568	292	153	76
1987	1233	539	598	306	170	77
1988	1332	531	568	289	169	74
1989	1239	535	630	305	174	86
1990	1098	519	628	314	172	88
1991	1019	530	614	302	170	82
1992	1315	694	607	386	239	143
1993	1631	810	635	401	270	171
1994	1645	824	689	463	293	173
1995	1369	649	726	415	276	148

Sources: Western Wood Products Association. 1971-1995. Inland F.O.B. price summary.

Table 3.7. Nominal prices for whitewood lumber (including lodgepole pine), western U. S. mills, 1974 -1995.

Year	shop and better	2 common and better	3 common and better	4 common and better	utility	5 common	MSR
	U. S. dollars per thousand Scribner board feet						
1974	-	225	103	98	91	40	-
1975	-	217	123	98	104	47	-
1976	-	233	154	131	133	51	-
1977	-	-	181	140	145	65	-
1978	-	-	210	170	165	90	-
1979	-	-	219	183	166	87	-
1980	-	-	187	162	142	86	-
1981	-	-	189	154	139	85	-
1982	-	-	165	131	128	81	-
1983	-	-	212	159	173	95	-
1984	-	350	195	151	145	83	230
1985	-	344	190	128	150	80	230
1986	-	360	204	151	167	81	237
1987	-	389	210	166	173	83	252
1988	-	386	217	232	170	90	252
1989	-	368	228	241	203	99	267
1990	-	395	219	207	202	95	259
1991	-	413	237	206	206	92	278
1992	-	469	289	249	273	124	306
1993	876	515	358	312	337	169	473
1994	962	623	395	317	374	155	-
1995	918	541	308	284	292	144	405

Sources: Western Wood Products Association. 1971-1995. Inland F.O.B. Price Summary.

Table 3.8. Production percentages for Douglas-fir lumber, Pacific Northwest coast mills, 1971-1995.

Year	C select	D select and shop	structural items	heavy framing	light framing	utility	economy	WWPA reported harvest, all grades
	-----	-----	-----	*Percent*	-----	-----	-----	*Scribner scale mbf*
1971	13.4	2.2	8.0	15.8	40.3	16.7	3.5	1,224,585
1972	10.9	2.0	10.1	15.8	38.4	18.1	3.8	1,413,467
1973	8.5	1.4	13.4	7.0	40.9	17.8	3.8	1,446,109
1974	7.2	1.2	12.4	17.1	41.7	15.9	4.6	1,523,405
1975	7.9	0.7	11.0	17.7	42.8	16.2	3.7	1,569,174
1976	8.2	0.8	12.3	17.7	41.6	15.1	4.4	1,832,619
1977	6.5	4.2	11.5	19.7	36.3	17.0	4.8	2,029,086
1978	5.2	4.3	11.1	19.6	38.6	16.3	4.9	2,030,353
1979	5.4	4.7	12.1	18.1	37.5	16.8	5.4	1,702,828
1980	5.8	4.5	11.5	21.3	35.2	16.8	4.9	1,515,924
1981	4.5	4.1	12.9	22.0	37.7	14.8	4.0	1,662,233
1982	4.5	4.3	12.3	22.3	38.1	14.6	3.9	1,551,419
1983	3.3	3.5	12.4	23.8	42.4	10.6	3.9	2,752,061
1984	2.6	3.4	15.3	22.5	42.8	9.4	4.0	3,168,494
1985	2.4	3.2	16.4	23.9	41.8	8.5	3.8	2,927,403
1986	2.1	2.3	15.6	24.0	43.7	8.6	3.6	3,584,260
1987	2.0	2.8	14.5	23.3	45.4	8.2	3.8	3,975,895
1988	1.8	2.1	16.7	21.8	46.2	7.1	4.3	3,691,263
1989	1.0	1.6	15.9	22.9	47.4	7.0	4.2	3,659,762
1990	1.0	1.5	16.1	22.5	47.9	6.5	4.5	3,038,613
1991	0.6	1.2	14.3	23.5	48.7	7.3	4.4	2,674,855
1992	0.3	1.0	11.6	24.3	51.9	6.6	4.2	2,507,869
1993	0.1	0.7	11.2	24.2	54.7	5.4	3.7	2,386,007
1994	0.1	0.8	11.5	23.5	55.0	5.3	3.8	2,700,841
1995	0.1	0.7	12.2	21.9	57.2	4.9	3.0	2,436,390

Sources: Haynes and Fight (1992) and Warren (1996)

Table 3.9. Production percentages for hem-fir lumber, Pacific Northwest coast mills, 1971-1995.

Year	C select	D select and shop	structural items	heavy framing	light framing	utility	economy	WWPA reported harvest, all grades
	---Percent---							*Scribner scale mbf*
1971	1.5	4.2	3.6	12.9	54.8	18.2	4.8	744,892
1972	1.1	4.5	3.2	12.9	53.6	19.4	5.3	873,074
1973	0.6	4.8	3.2	11.4	54.5	20.5	5.0	758,354
1974	0.5	3.7	3.6	10.6	55.4	19.8	6.4	631,208
1975	0.9	5.3	3.6	8.8	54.5	21.2	5.8	670,315
1976	0.7	5.5	3.4	10.7	53.1	19.8	6.9	750,733
1977	1.4	4.8	6.2	8.7	56.7	15.0	7.2	933,315
1978	1.5	5.2	7.3	7.8	55.3	14.6	8.3	970,882
1979	1.5	5.1	7.7	5.3	58.3	13.8	8.3	835,574
1980	1.4	5.4	7.5	4.9	60.5	14.4	5.9	597,383
1981	1.2	5.4	6.2	7.8	58.0	14.6	6.8	582,672
1982	0.4	4.9	6.0	7.2	59.1	17.1	5.3	577,243
1983	0.4	4.0	5.6	8.8	61.6	13.8	5.8	857,819
1984	0.4	4.2	5.3	12.9	60.8	10.0	6.3	959,799
1985	0.4	4.0	3.3	15.0	63.0	8.4	6.0	830,607
1986	0.4	2.5	3.1	16.2	64.0	8.4	5.4	1,000,702
1987	0.3	2.3	2.9	14.8	64.9	9.3	5.3	1,011,504
1988	0.3	2.2	3.2	14.2	66.4	8.2	5.5	946,868
1989	0.3	2.0	4.2	16.9	63.6	7.4	5.8	903,323
1990	0.2	1.5	5.5	16.4	62.8	7.5	6.1	784,600
1991	0.2	1.6	4.8	16.3	62.3	8.7	6.2	696,775
1992	0.1	1.5	5.8	17.3	62.5	6.9	6.0	922,463
1993	0.0	0.8	6.7	17.4	61.8	7.2	6.1	977,364
1994	0.0	0.6	4.1	19.0	62.6	6.7	7.0	1,180,705
1995	0.0	0.5	3.7	22.9	59.1	7.6	6.2	1,001,187

Sources: Haynes and Fight (1992) and Warren (1996)

Table 3.10. Production percentages for ponderosa pine lumber, western U. S. mills, 1971-1995.[a]

	4/4 selects and #1 shop					5/4 and thicker moulding and shops					4/4 commons and 8/4 standard and better				low value		
Year	C and better 6-12 in	D 12 in	C and btr. 4 in, D 6-10 in	D 4 in	#1 shop	Mldg. and better	#1 shop	#2 shop	#3 shop	shopout	2 com. 12 in	2com. 4-10 in	3 com., 6-12 in 8/4 dimen.	3 com., 4 in 4 com., 4-12 in	#3 and utility	5 com. and economy	WWPA reported harvest, all grades
	-----	-----	-----	-----	-----	-----	-----	-----	Percent	-----	-----	-----	-----	-----	-----	-----	*Scribner scale mbf*
1971	1.6	0.5	1.2	1.1	3.8	7.1	4.3	14.3	8.6	5.6	4.3	2.4	29.2	11.2	2.4	2.3	1,995,778
1972	1.5	0.5	1.1	1.3	4.1	6.6	4.0	14.8	10.4	5.2	3.7	2.0	30.1	10.0	2.5	2.2	2,029,950
1973	1.3	0.4	0.9	1.4	3.9	7.4	4.1	14.1	10.0	4.9	3.2	1.8	32.4	8.9	2.9	2.3	1,961.374
1974	1.3	0.4	0.9	1.5	4.0	6.4	3.4	12.7	9.3	5.0	3.1	2.2	34.6	10.3	2.3	2.6	1,691,282
1975	1.3	0.4	0.8	1.6	3.9	6.4	3.7	13.8	9.9	4.8	3.0	2.1	33.3	9.9	2.4	2.4	1,842,488
1976	1.3	0.4	0.9	1.5	4.1	6.5	3.7	14.2	11.2	5.2	3.0	2.4	31.7	10.0	1.9	2.2	2,046,066
1977	1.1	0.4	0.7	1.1	3.5	6.0	3.4	13.9	12.4	7.0	2.9	5.0	29.2	9.5	1.8	2.1	2,249,864
1978	0.9	0.3	0.6	1.1	2.8	5.6	2.9	13.0	13.3	7.2	2.7	5.3	30.5	9.2	2.2	2.3	2,271,539
1979	0.9	0.3	0.6	1.2	3.3	5.6	3.0	13.2	12.6	5.6	3.0	6.0	29.8	10.5	2.0	2.5	1,849,683
1980	1.0	0.4	0.8	1.3	3.3	6.5	3.2	14.4	12.8	4.7	3.2	6.9	27.3	9.9	2.1	2.3	1,614,864
1981	1.0	0.3	0.8	1.1	3.3	5.9	3.1	14.8	13.4	4.7	3.9	8.7	25.7	10.0	1.5	1.8	1,474,420
1982	1.1	0.3	0.7	0.9	3.1	6.8	3.2	15.7	13.5	5.1	4.2	8.0	26.9	8.8	1.3	1.6	1,488,103
1983	1.0	0.3	0.7	0.9	2.8	5.8	3.3	17.2	15.6	5.3	3.9	7.8	24.4	7.1	1.2	1.5	1,876,743
1984	1.0	0.3	0.6	0.9	2.7	5.3	3.5	17.6	15.4	4.2	4.1	7.2	26.8	7.1	1.6	1.7	1,970,046
1985	0.9	0.3	0.6	0.9	2.7	5.1	3.4	18.2	16.2	4.1	3.8	7.2	26.7	7.0	1.4	1.4	2,018,896
1986	1.0	0.3	0.6	0.8	2.8	4.9	3.3	17.9	16.6	4.5	4.3	6.7	27.6	6.1	1.4	1.3	2,164,591

Table 3.10. continued.

1987	0.9	0.2	0.4	0.7	2.4	5.7	3.1	17.9	17.5	4.7	4.0	6.0	28.1	5.3	1.6	1.4	2,331,497
1988	0.8	0.2	0.4	0.7	2.7	5.8	2.7	17.2	18.0	5.4	3.9	5.5	28.4	5.2	1.7	1.5	2,252,696
1989	0.6	0.2	0.3	0.7	2.2	5.6	2.9	17.8	19.9	6.7	3.8	5.8	25.9	5.0	1.2	1.4	2,204,308
1990	0.6	0.1	0.3	0.6	2.0	5.3	2.7	17.8	21.3	7.0	3.7	5.4	25.0	5.2	1.1	1.7	2,045,830
1991	0.7	0.1	0.3	0.7	2.1	6.0	2.9	17.8	22.7	7.8	3.6	5.6	22.0	4.7	1.3	1.6	1,789,289
1992	0.5	0.1	0.3	0.7	1.8	5.9	2.5	16.5	23.2	9.8	3.1	7.0	20.9	4.9	1.1	1.4	1,643,951
1993	0.3	0.1	0.2	0.5	1.6	4.7	1.8	12.6	21.5	14.8	3.3	8.9	21.9	5.2	1.4	1.2	1,844,062
1994	0.3	0.1	0.2	0.5	1.4	4.1	1.5	10.8	20.8	14.7	3.4	10.4	23.5	5.5	1.3	1.5	1,712,968
1995	0.3	0.1	0.2	0.4	1.5	3.8	1.3	10.2	21.0	15.0	4.0	11.9	22.1	5.8	1.3	1.1	1,519,049

[a] Before 1979, volumes and percentages include ponderosa pine milled in the Rocky Mountain region.
Sources: Haynes and Fight (1992) and Warren (1996)

Table 3.11. Production percentages for sugar pine lumber, western U. S. mills, 1971-95.

Year	4/4 selects and #1 shop: C and better 6-12 in	4/4 selects and #1 shop: C and btr. 4 in, D 6-12 in	4/4 selects and #1 shop: D 4 in	4/4 selects and #1 shop: #1 shop	5/4 and thicker moulding and shops: Mldg. and better	5/4 and thicker moulding and shops: #1 shop	5/4 and thicker moulding and shops: #2 shop	5/4 and thicker moulding and shops: #3 shop	5/4 and thicker moulding and shops: shopout	4/4 commons and 8/4 standard and better: 2 com. 12 in	4/4 commons and 8/4 standard and better: 2com. 4-10 in	4/4 commons and 8/4 standard and better: 3 com., 6-12 in 8/4 dimen.	4/4 commons and 8/4 standard and better: 3 com., 4in 4 com., 4-12 in, #3 and utility	low value: 5 common economy	WWPA reported harvest, all grades
	Percent														*Scribner scale mbf*
1971	4.6	2.8	4.1	5.3	10.2	8.2	18.0	9.0	2.1	3.9	6.7	14.3	9.2	1.5	184,048
1972	4.7	2.5	3.6	4.9	9.5	7.9	17.4	10.0	3.6	2.9	8.2	14.3	9.1	1.4	166,078
1973	4.4	2.5	4.4	4.5	11.3	6.6	14.3	10.1	2.9	2.4	8.4	16.8	9.8	1.6	146,489
1974	4.3	2.5	4.8	4.2	11.1	6.2	14.8	10.2	3.1	2.5	6.0	18.2	10.2	1.8	123,523
1975	3.4	1.9	4.2	3.5	12.1	7.4	17.4	11.1	2.2	2.2	5.7	16.9	10.2	1.8	144,370
1976	3.1	1.9	3.7	3.8	13.3	6.7	16.5	11.4	2.6	1.9	6.5	17.3	9.6	1.8	146,440
1977	3.0	1.5	2.9	3.2	12.2	6.7	17.1	15.2	5.2	1.0	6.3	15.4	8.7	1.6	163,370
1978	2.1	1.2	2.7	3.2	11.7	5.0	15.4	15.5	6.8	1.2	6.5	18.2	9.0	1.6	170,299
1979	1.9	1.0	2.8	3.2	10.8	4.9	15.5	17.7	6.8	1.1	5.8	17.5	9.4	1.5	143,880
1980	1.7	0.8	2.7	2.8	10.7	3.7	13.7	18.8	7.7	1.0	6.9	17.7	10.1	1.6	127,687
1981	2.0	1.3	2.0	2.3	10.7	4.5	15.1	16.8	7.0	0.7	7.9	18.0	10.1	1.6	114,435
1982	3.1	1.5	2.7	2.4	11.4	4.2	15.5	15.8	5.0	0.7	8.4	19.0	9.3	1.2	95,251
1983	2.7	1.2	2.1	2.3	10.9	5.2	18.8	18.0	6.9	0.7	7.2	15.8	7.2	1.1	141,050
1984	2.5	1.5	2.4	2.5	9.6	4.5	17.3	17.9	6.8	0.6	7.9	17.5	7.9	1.1	189,252
1985	2.1	1.6	2.3	2.2	8.4	4.6	17.4	17.7	8.1	0.6	8.3	18.0	7.2	1.4	209,026
1986	2.4	1.2	1.7	2.3	8.7	4.6	18.0	18.2	8.0	0.7	10.1	17.4	5.8	0.9	209,392

Table 3.11. continued.

1987	1.8	1.1	1.7	1.8	8.6	4.1	17.2	19.9	10.9	0.5	9.0	17.0	5.4	1.0	217,201
1988	1.5	0.8	1.5	1.5	6.8	3.5	16.4	19.2	10.1	0.4	8.5	21.9	6.9	0.7	273,305
1989	0.9	0.5	1.6	1.7	6.3	3.2	17.9	22.4	11.6	0.4	7.1	20.3	5.4	0.5	258,242
1990	1.1	0.6	1.9	1.6	5.5	3.1	18.5	24.6	12.4	0.3	8.1	16.9	4.7	0.5	233,003
1991	1.0	0.5	1.5	1.6	6.2	3.5	19.4	23.9	11.0	0.4	7.3	17.8	5.5	0.5	243,516
1992	1.1	0.4	1.2	1.5	8.6	3.1	19.0	26.3	12.2	0.3	7.9	13.7	4.2	0.4	212,008
1993	0.3	0.2	0.9	1.4	9.5	2.6	13.7	23.0	13.7	0.2	11.0	17.8	4.7	1.0	165,379
1994	0.6	0.3	1.0	1.2	9.5	2.4	12.9	23.1	13.3	0.0	10.8	18.9	4.9	1.2	137,121
1995	0.5	0.3	0.9	1.2	7.7	2.0	11.8	22.8	12.5	0.0	16.1	17.8	5.3	1.2	92,761

Sources: Western Wood Products Association. 1971-1995. Inland F.O.B. Price Summary.

Table 3.12. Production percentages for western white pine lumber, western U. S. mills, 1971-1995.

Year	D select and better	shop and better	2 common	3 common	4 common	5 common	WWPA reported harvest, all grades
	Percent						Scribner scale mbf
1971	7.3	3.6	31.2	37.6	18.4	1.8	302,570
1972	7.1	4.6	28.7	39.5	18.4	1.7	274,790
1973	6.8	4.8	28.6	40.7	17.4	1.9	249,249
1974	6.6	4.2	28.3	40.9	17.6	2.4	192,589
1975	6.6	2.9	29.5	43.9	15.8	1.4	222,122
1976	6.2	3.0	31.4	43.0	14.9	1.5	216,576
1977	5.7	2.8	31.5	43.3	15.4	1.3	205,918
1978	5.0	2.1	28.0	44.7	18.0	2.2	158,205
1979	4.6	2.8	27.6	46.3	17.0	1.6	152,497
1980	5.5	3.7	29.4	44.7	15.6	1.1	135,253
1981	6.0	3.0	30.7	42.2	16.9	1.1	114,574
1982	6.0	3.5	33.0	41.6	15.1	0.8	88,145
1983	5.7	3.8	33.7	41.2	14.6	1.0	118,841
1984	5.5	3.9	36.8	39.5	13.4	0.9	113,666
1985	6.1	5.1	37.5	37.4	13.3	0.6	99,002
1986	6.7	4.0	42.4	36.4	10.1	0.5	90,195
1987	6.4	5.3	41.9	34.8	10.9	0.6	89,700
1988	6.7	7.8	37.2	34.2	13.0	1.1	59,799
1989	9.9	11.1	18.5	43.7	15.8	1.0	35,310
1990	8.9	9.4	18.3	43.1	19.7	0.6	29,794
1991	8.4	11.9	18.3	39.8	21.0	0.6	25,516
1992	4.6	5.8	42.9	36.4	9.7	0.6	55,827
1993	4.1	5.7	41.5	36.9	10.8	0.9	43,849
1994	2.7	4.2	48.6	32.9	10.4	1.2	36,293
1995	3.0	3.9	47.9	35.8	8.9	0.6	21,393

Sources: Western Wood Products Association. 1971-1995. Inland F.O.B. Price Summary.

Table 3.13. Production percentages for whitewood (including lodgepole pine), western U. S. mills, 1974-1995.

Year	shop and better	2 common and better	3 common and better	4 common and better	utility	5 common	MSR[a]	WWPA reported volumes, all
	----------Percent----------							*Scribner scale mbf*
1974	0.0	0.2	89.1	1.0	3.1	6.6	0.0	205,638
1975	0.0	0.3	79.5	1.9	10.4	8.0	0.0	434,013
1976	0.0	0.3	79.1	1.4	11.4	7.8	0.0	550,365
1977	0.0	0.0	80.6	2.0	10.6	6.8	0.0	632,493
1978	0.0	0.0	82.1	2.3	7.7	8.0	0.0	584,476
1979	0.0	0.0	80.4	2.8	7.7	9.1	0.0	601,749
1980	0.0	0.0	79.3	3.4	8.3	9.1	0.0	413,236
1981	0.0	0.0	78.8	4.2	7.9	9.0	0.0	419,474
1982	0.0	0.0	78.8	4.5	7.0	9.8	0.0	343,111
1983	0.0	0.0	79.8	3.7	8.0	8.6	0.0	470,483
1984	0.0	6.1	71.7	4.6	8.7	8.5	0.3	532,148
1985	0.0	10.2	70.5	4.9	6.5	7.3	0.6	526,174
1986	0.0	12.0	69.2	3.4	6.3	8.1	1.0	600,912
1987	0.0	9.5	73.6	2.8	4.5	8.8	0.8	750,763
1988	0.0	11.9	69.6	3.9	4.7	9.3	0.6	759,901
1989	0.0	14.0	67.1	5.0	4.6	9.2	0.2	814,907
1990	0.0	15.3	65.1	4.4	5.6	9.7	0.0	733,890
1991	0.0	18.4	60.7	5.5	4.8	8.4	2.3	647,762
1992	0.0	15.4	57.1	11.9	5.8	6.8	3.0	735,287
1993	0.5	5.9	61.9	9.6	9.4	8.4	4.4	439,365
1994	0.2	3.6	66.1	8.2	9.8	12.2	0.0	424,090
1995	0.2	2.6	62.4	9.1	12.7	11.1	1.9	304,567

[a] machine stress-rated

Sources: Western Wood Products Association. 1971-1995. Inland F.O.B. Price Summary.

Table 3.14. Producer price multipliers applied to nominal lumber prices for indexing to 1990 U. S. dollar prices.

Year	Adjustment Multiplier
1971	3.173
1972	3.063
1973	2.873
1974	2.354
1975	2.109
1976	1.983
1977	1.853
1978	1.729
1979	1.530
1980	1.316
1981	1.189
1982	1.158
1983	1.145
1984	1.121
1985	1.117
1986	1.158
1987	1.129
1988	1.089
1989	1.038
1990	1.000
1991	0.994
1992	0.986
1993	0.973
1994	0.959
1995	0.923

Source: Office of the President. 1996. Economic Report of the President, table B-63.

resumption of this long-term trend or an extended cycle of high prices induced by political events - a cycle which is possibly on the downside since 1994. During the extended period of overall higher lumber prices (1986-1995), average annual real prices for the coastal region lumber never exceeded average annual real prices for the banner years 1973 and 1979.

3.3.1. Douglas-fir Trends

Douglas-fir remains the mainstay timber species of the Pacific Northwest Coast lumber industry. Production of high-quality Douglas-fir lumber in the Pacific Northwest is indicative of trends in Pacific Northwest lumber manufacturing (figure 3.1.). High-quality grades such as selects and shops declined both in proportional and absolute amounts throughout the period 1971-1995 (table 3.8.). In the period 1991-1995, 1.1 percent of lumber production was in select and shop categories in contrast to more than 11 percent in the early 1970's. Production has become increasingly concentrated in the mid-value light and heavy framing grades. Commodity production and engineered products have replaced the high-value products. Framing grades comprised more than 75 percent of total production in 1991-1995 in contrast to 56 percent in the early 1970's. At the same time, a move to middle grades is also occurring from below. Production volume of lumber in lower-valued utility grades has also declined by half in the period 1971-1995, while economy grade volumes have remained roughly constant.

Highest quality lumber grades sustained a continual real price increase from 1985 to 1994 (table 3.15.), but 1990s real prices have yet to exceed 1979 real prices, the high for the period, with one exception. The category for D select and shop lumber is the only category to have had an all-time price maximum during the period 1991-1995. Select and shop grades, structural items, and heavy framing lumber offered price premiums above the average Douglas-fir lumber prices for the coastal Pacific Northwest. The average real

Figure 3.1. Douglas-fir lumber grade composition, Pacific Northwest coast mills, 1971-1995.

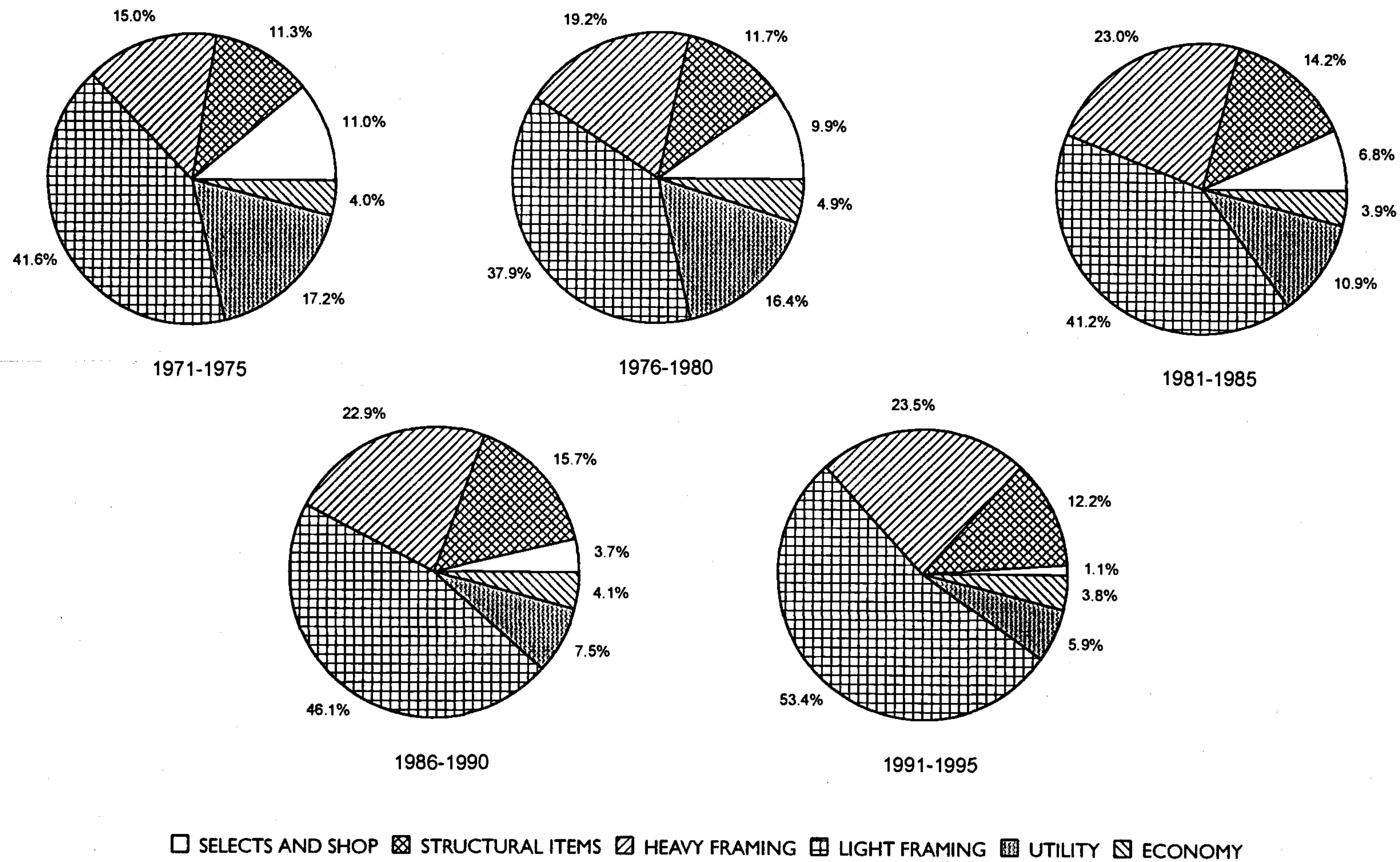


Table 3.15. Real prices for Douglas-fir lumber, Pacific Northwest coast mills, 1971-1995.

Year	C select	D select and shop	structural items	heavy framing	light framing	utility	economy
	in 1990 U. S. dollars per thousand Scribner board feet						
1971	723	463	400	387	333	235	105
1972	858	502	438	432	386	285	126
1973	1353	621	603	569	463	336	193
1974	1116	560	560	433	332	193	111
1975	856	475	390	348	293	177	95
1976	964	547	454	430	345	218	97
1977	934	634	535	398	398	274	113
1978	1025	702	562	683	406	294	149
1979	1363	734	627	511	376	274	132
1980	1222	666	480	357	272	197	112
1981	888	506	391	313	229	163	99
1982	750	434	328	229	184	146	90
1983	785	488	300	254	230	186	100
1984	771	456	279	250	212	154	81
1985	749	458	278	252	212	146	76
1986	841	469	278	265	221	153	78
1987	945	464	290	291	233	156	74
1988	1010	516	324	310	239	150	93
1989	1119	522	337	342	255	174	114
1990	1236	521	305	310	232	156	102
1991	1193	532	314	304	229	157	100
1992	1332	568	343	344	269	202	121
1993	1165	787	497	503	382	287	170
1994	1356	721	459	465	369	282	142
1995	1081	645	413	408	304	207	131

Prices are FOB computed as volume-weighted averages of green and dry surfaced and rough grades.

Sources: Haynes and Fight (1992) and Warren (1996)

value of Douglas-fir lumber spiked upward in 1993 with a 40 percent increase over the 1992 average real price (Sohngen and Haynes 1994). In 1994-1995 real prices dropped to values still substantially higher than per-spike values (figure 3.2. and table 3.15.).

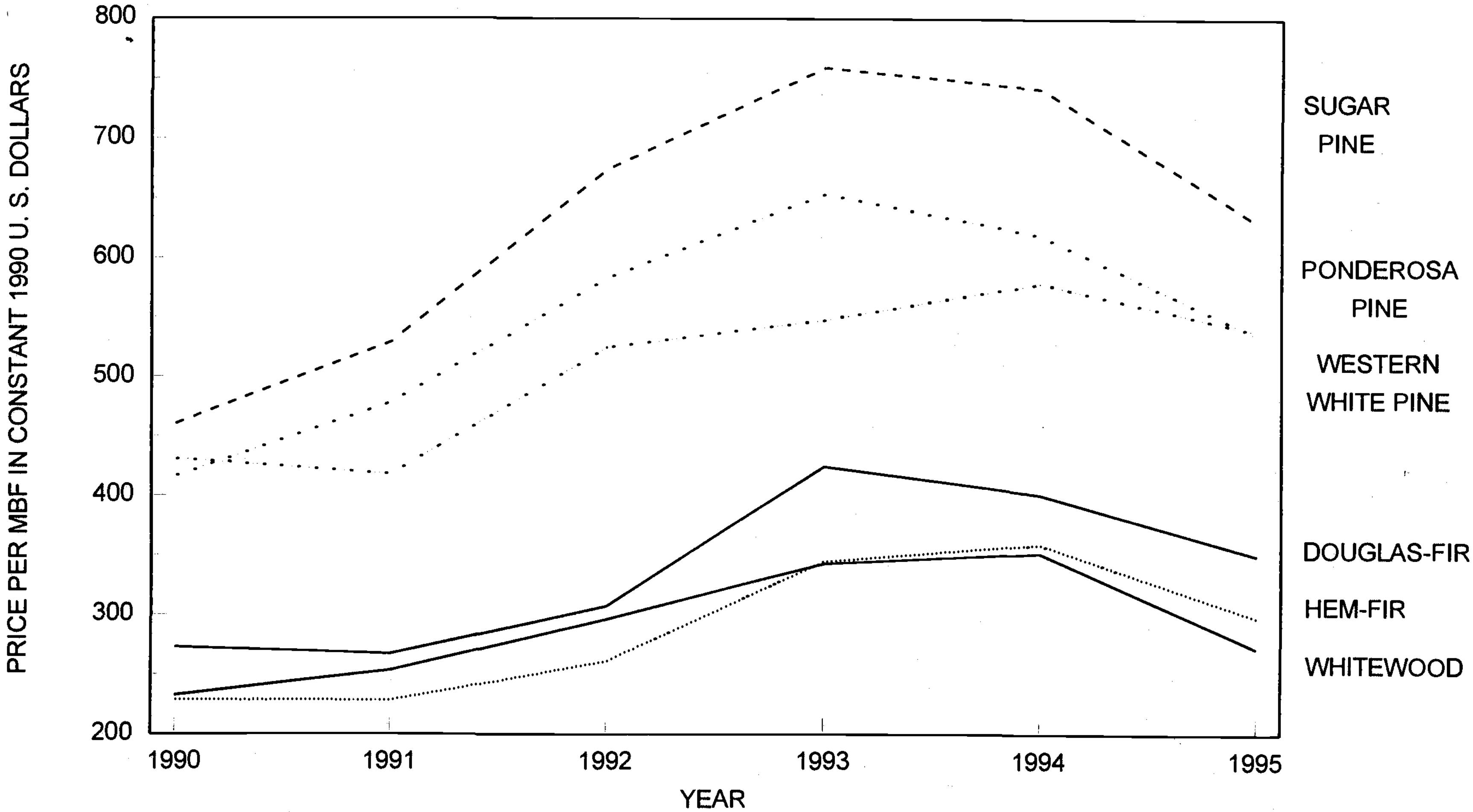
3.3.2. Coast Hem-Fir Trends

Trends in the composition of hem-fir lumber production (figure 3.3. and table 3.16.) largely reflect trends occurring with Douglas-fir. Select and shop grades have virtually disappeared in hem-fir lumber production. The long-term decline in the proportion of utility grade material also continues. Production volume of utility lumber has also declined by half in the period 1971-1995. Economy grade lumber has remained relatively constant in proportion but is subject to substantial price swings. The most striking difference is the small amount of hem-fir in structural items. Here the difference in physical properties of hem-fir and Douglas-fir appears to favor Douglas-fir. Hem-fir has remained a less valuable resource overall with a greater proportion of the lumber resource produced in heavy framing and lower grade categories as compared to Douglas-fir. In the period 1983-1995, prices for hem-fir lumber in all lumber grade categories except economy grade remained lower than prices for comparable grades of Douglas-fir lumber.

3.3.3. Ponderosa Pine Trends

Ponderosa pine lumber production exceeds lumber production from all other pine species together in the western United States (Western Wood Products Association 1995c). Division of ponderosa pine lumber into sixteen grade categories reflects this large and diversified production. The production capacity for ponderosa pine lumber has not mirrored the growth seen for coast Douglas-fir since 1982. Between 1991 and 1995, total

Figure 3.2. Lumber prices for commercial timber species in the Pacific Northwest, 1990-1995.



Source: Western Wood Products Association, Year End Totals, 1990-1995

Figure 3.3. Hem-fir lumber grade composition, Pacific Northwest coast mills, 1971-1995.

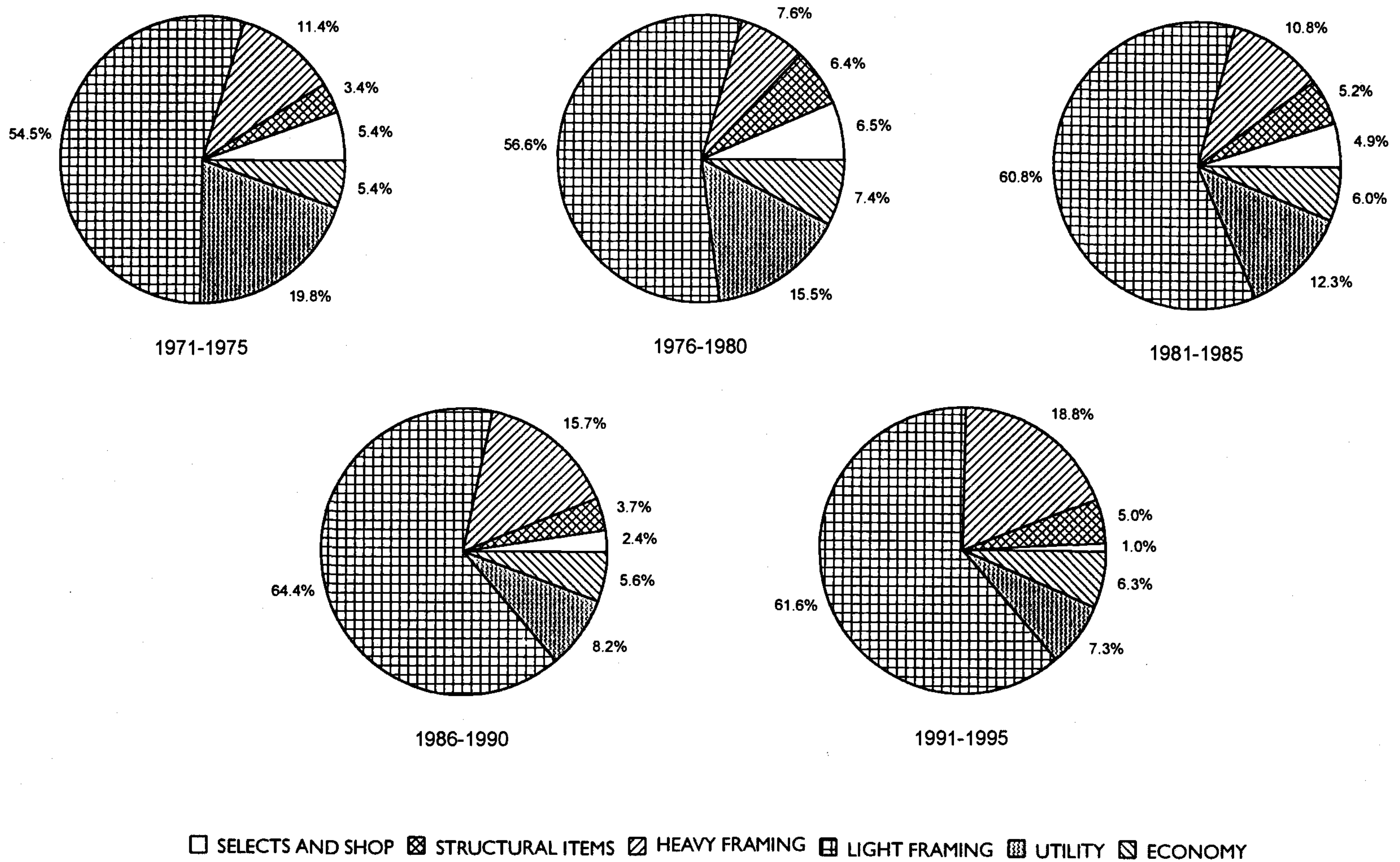


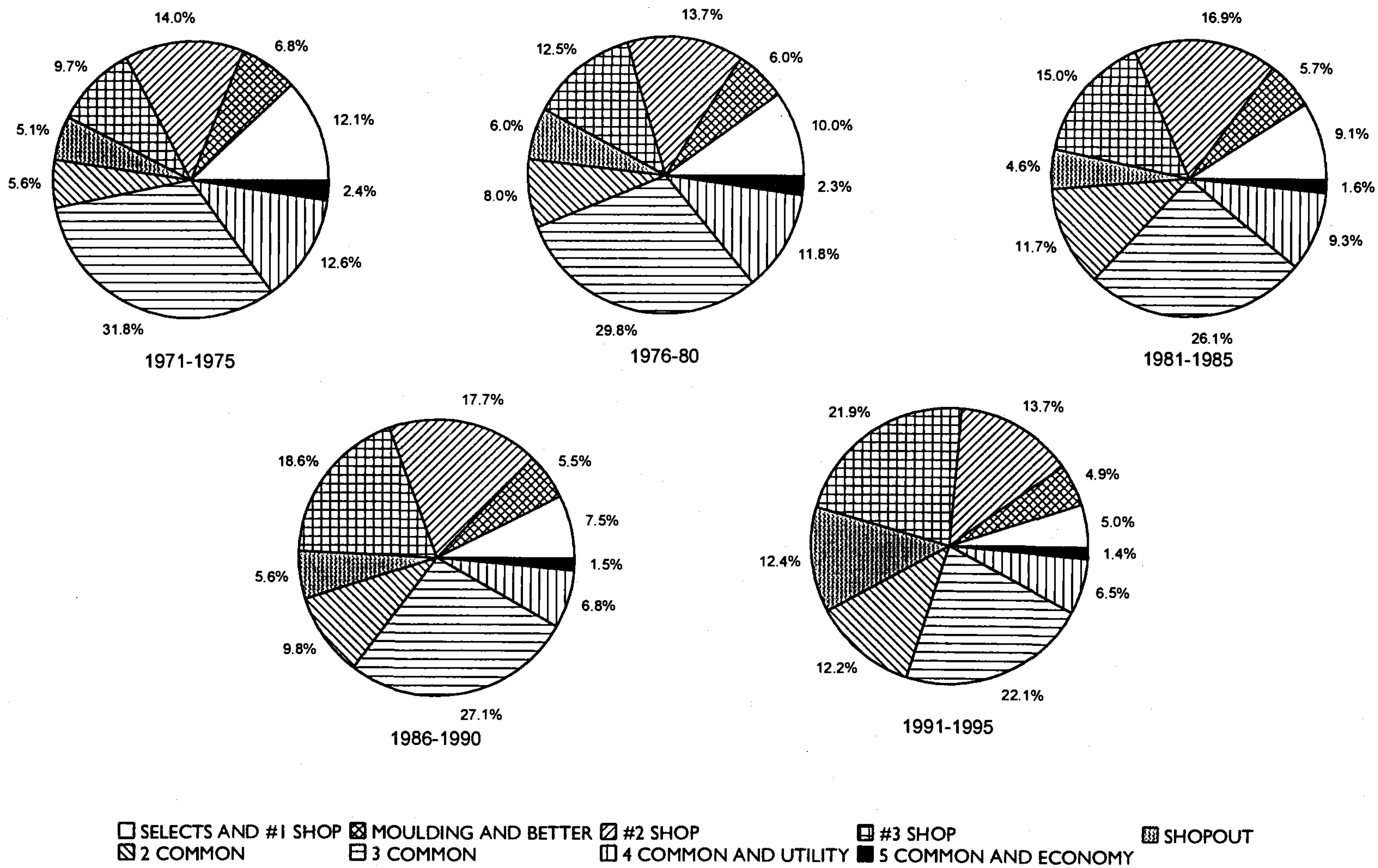
Table 3.16 . Real prices for hem-fir lumber, Pacific Northwest coast mills, 1971-1995.

Year	C select	D select and shop	structural items	heavy framing	light framing	utility	economy
	in 1990 U. S. dollars per thousand Scribner board feet						
1971	657	438	400	365	320	225	108
1972	738	463	453	423	374	276	126
1973	988	601	555	520	451	325	178
1974	1036	548	421	421	330	191	104
1975	740	439	346	340	281	167	89
1976	847	512	399	408	325	210	95
1977	839	532	424	437	356	250	107
1978	1015	596	448	442	384	283	147
1979	1034	612	442	462	358	245	119
1980	945	533	338	322	257	174	103
1981	786	430	272	290	218	156	94
1982	824	369	234	242	183	142	81
1983	844	442	281	275	235	179	111
1984	766	390	254	256	210	143	89
1985	712	376	252	259	211	137	88
1986	702	397	280	287	228	149	87
1987	678	467	308	323	243	148	86
1988	690	502	297	315	241	149	97
1989	745	484	284	309	243	161	109
1990	820	500	270	283	224	150	97
1991	795	460	281	275	229	146	95
1992	871	481	317	308	262	185	127
1993	-	623	421	431	365	232	174
1994	-	572	418	434	368	257	157
1995	-	544	329	366	288	193	142

Prices are FOB computed as volume-weighted averages of green and dry surfaced and rough grades.

Sources: Haynes and Fight (1992) and Warren (1996)

Figure 3.4. Ponderosa pine lumber grade composition, western U. S. mills, 1971-1995.



western USA production of ponderosa pine has fallen by nearly one-third. In the coastal Pacific Northwest region, timber comes primarily from southwestern Oregon.

As with coast hem-fir and Douglas-fir, higher-valued ponderosa pine select and #1 shop grade categories comprise an ever smaller part of total production (figure 3.4. and table 3.11.) between 1971 and 1995. Less than four percent of the total lumber production for these grades in 1995 contrasts with 11.4 percent in 1971. Loss of product quality has also changed the composition of ponderosa pine lumber supply. Moulding and better and #2 shop grades have had their all-time lowest share of ponderosa pine lumber production since 1990. Lower value #3 shop, shopout, and 2 common grades were the only categories with higher percentages in the period 1990-1995 than in the previous twenty years. Among the grades with increasing volumes of lumber, #3 shop and 2 common grades had annual average prices higher than the average annual prices for total eastside lumber. Despite loss of quality, ponderosa prices 1993-94 recorded the highest real prices for the period 1971-1995 for 2 common, all shop, moulding, and select grade categories. Prices for grades of ponderosa pine lumber below the eastside average prices rose considerably during the two-year period but did not exceed real price levels in the banner year 1973.

3.3.4. Sugar Pine Trends

The supply of sugar pine lumber has historically amounted to about one-tenth of the board-foot lumber volume (table 3.11.) of ponderosa pine (table 3.10.) and has tracked with the production volume and composition of ponderosa pine lumber (figures 3.4. and 3.5.). Sugar pine lumber volumes have experienced relatively steeper cycles in production fluctuation than for ponderosa pine. Since the all-time high production of sugar pine lumber in 1987-1988, production has declined by two-thirds to the 1995 level. For the period 1971-1995, lowest lumber production occurred in 1995.

Table 3.17. Real prices for ponderosa pine lumber, western U. S. mills, 1971-1995.

	4/4 selects and #1 shop					5/4 and thicker moulding and shops					4/4 commons and 8/4 standard and better				low value	
Year	C and better 6-12 in	D 12 in	C and btr. 4 in, D 6-10 in	D 4 in	#1 shop	Mldg. and better	#1 shop	#2 shop	#3 shop	shopout	2 com. 12 in	2com. 4-10 in	3 com., 6-12 in 8/4 dimen.	3 com., 4 in 4 com., 4-12 in	#3 and utility	5 com. and economy
	1990 U. S. dollars per thousand Scribner board feet															
1971	1218	974	831	625	431	955	698	501	422	270	425	359	295	238	232	121
1972	1232	023	870	643	481	962	757	567	481	328	505	423	371	309	276	153
1973	1376	1178	1060	819	595	1126	845	667	560	457	695	595	471	414	333	224
1974	1440	1295	1174	718	494	1010	739	593	490	313	635	497	332	252	172	134
1975	1363	1152	958	542	365	1006	586	435	323	205	519	397	264	186	154	99
1976	1404	1219	880	662	462	1053	789	646	492	284	539	434	329	256	194	115
1977	1512	1343	952	667	519	1017	841	711	530	321	613	504	363	271	228	133
1978	1730	1566	1160	845	603	1614	909	799	572	356	645	569	401	318	249	169
1979	2139	1920	1536	814	509	1461	847	736	465	321	675	549	402	281	222	147
1980	1562	1138	803	528	434	1070	722	622	405	267	592	380	312	217	161	114
1981	1320	1147	723	555	396	971	700	605	422	259	458	331	291	195	151	106
1982	1375	1002	706	464	382	941	636	548	357	235	521	335	274	191	141	101
1983	1391	1608	755	588	416	1210	758	653	459	258	444	349	254	183	178	103
1984	1528	1304	812	559	413	1064	697	567	391	228	484	358	263	167	139	93
1985	1634	964	870	565	382	1214	686	556	409	228	509	348	232	160	142	84
1986	1747	1354	1182	757	736	1266	797	667	468	240	498	376	263	189	151	91

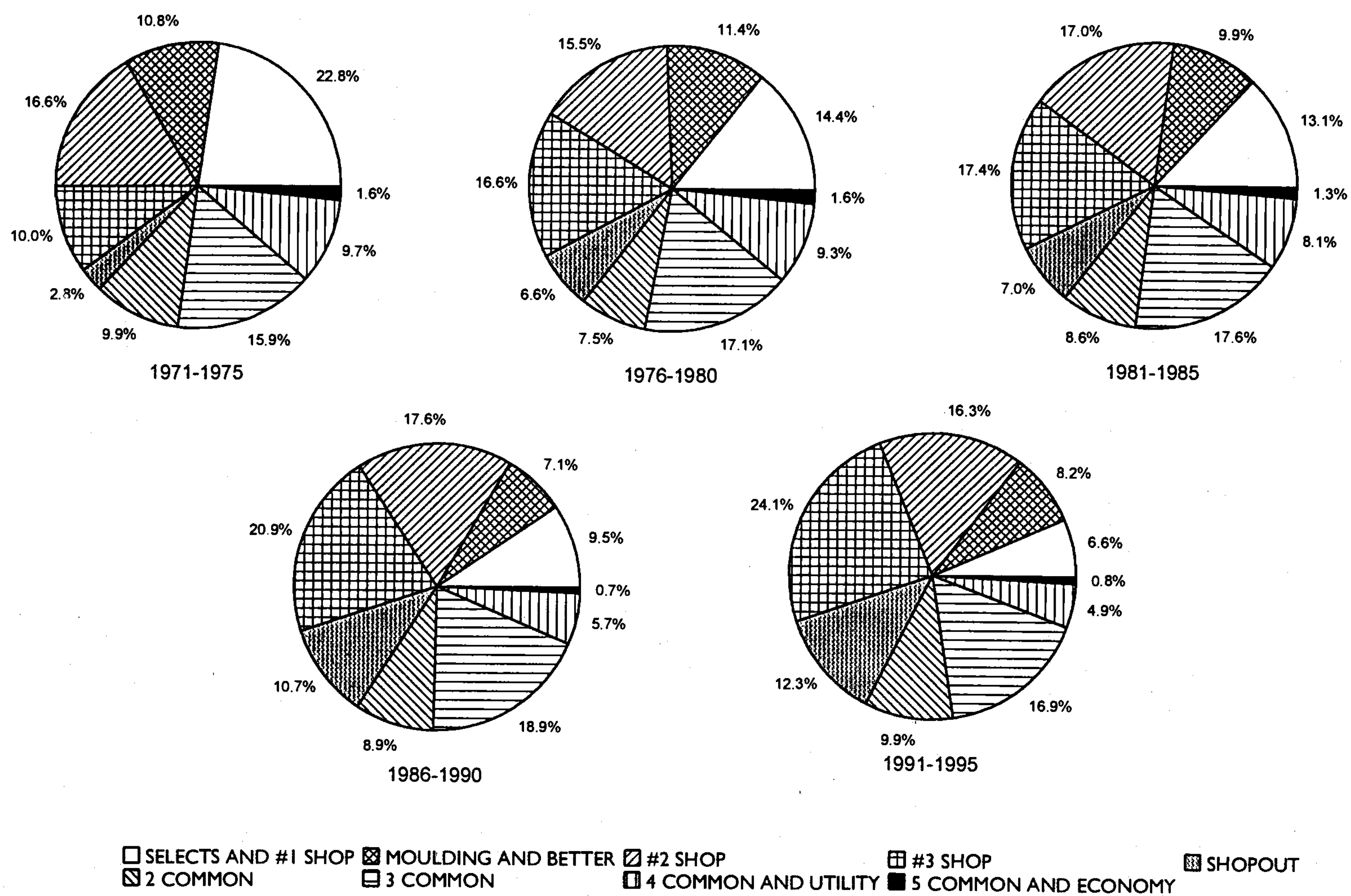
Table 3.17. continued.

1987	1764	1508	1228	793	499	1474	860	727	466	253	505	414	279	198	148	89
1988	2061	1645	1172	751	492	1397	813	681	448	249	550	395	268	190	149	95
1989	1873	1580	1054	768	454	1313	757	611	450	268	552	343	271	196	161	109
1990	1478	1453	996	683	435	1051	677	542	414	247	534	356	248	187	145	99
1991	1327	1251	906	650	422	1083	790	651	514	257	520	370	270	183	146	98
1992	1725	1464	1179	844	614	1352	957	833	622	330	677	417	332	223	193	131
1993	2139	1859	1469	992	681	1904	1157	1031	721	435	687	485	371	281	243	169
1994	2252	2248	1263	844	768	1682	1099	976	673	430	770	546	396	290	244	151
1995	1741	1829	1010	680	507	1376	1005	897	610	378	641	468	339	232	198	146

Prices are F.O.B. computed as volume-weighted averages of green and dry surfaced and rough grades.

Sources: Haynes and Fight (1992) and Warren (1996)

Figure 3.5. Sugar pine lumber grade composition, western U. S. mills, 1971-1995.



Grade groupings of sugar pine lumber correspond for the most part with those used for ponderosa pine. Fourteen grades of sugar pine lumber instead of sixteen grades as with ponderosa pine are considered here. D select, 12 in lumber has been merged into the C and better, 4 in, and D select, 4-10 in; utility items are incorporated into the category comprised of 4 common, 4-12 in, and # 3 lumber.

The value of the sugar pine production has been historically more valuable than any other species considered here (figure 3.2. and table 3.18.). Its physical properties and appearance make the species highly marketable. Since 1992, the average value of sugar pine lumber has averaged a hundred dollars more per thousand board feet of ponderosa pine lumber. In the period 1990-1995, higher-value grade categories of sugar pine lumber were consistently more valuable than comparable ponderosa pine grade categories. Low-value grades of sugar pine lumber have recently commanded prices equal to or lower than ponderosa pine lumber. This represents a change from 1971 when all grades of sugar pine were more valuable than ponderosa pine.

3.3.5. Western White Pine Trends

Western white pine lumber represents a nearly exhausted resource in the western United States (table 3.12.). Volume of timber production has declined steadily since 1971 when the highest volume for the period 1971-1995 was recorded. Much lumber production came from salvaged logs harvested after mortality caused by white pine blister rust (Snellgrove and Cahill 1980). The proportional loss of select grade lumber is not as steep as for other species, but absolute volume of high-value select grades is very small. As with the previous two pine species, greatest increase in proportion of lumber in the last 25 years has occurred in 2 common grades (figure 3.6.). For 2 common grade, western white pine ranks with sugar pine in value, above ponderosa pine (tables 3.17. through 3.19.).

Table 3.18. Real prices for sugar pine lumber, western U. S. mills, 1971-1995.

	4/4 selects and #1 shop				5/4 and thicker moulding and shops					4/4 commons and 8/4 standard and better				low value
Year	C and better 6-12 in	C and btr. 4 in, D 6-12 in	D 4 in	#1 shop	Mldg. and better	#1 shop	#2 shop	#3 shop	shopout	2 com. 12 in	2com. 4-10 in	3 com., 6-12 in 8/4 dimen.	3 com., 4in 4 com., 4-12 in, #3 and utility	5 common economy
	1990 U. S. dollars per thousand Scribner board feet													
1971	1270	973	709	444	980	718	525	422	336	592	441	308	241	122
1972	1325	1064	760	499	1009	781	591	479	378	657	505	378	303	148
1973	1518	1271	927	646	1186	870	698	593	595	776	734	527	417	261
1974	1533	1336	814	500	1046	779	612	534	506	680	672	373	247	159
1975	1436	1175	636	336	1055	621	474	372	384	607	563	298	195	102
1976	1479	1093	835	458	1083	799	668	525	415	735	584	374	262	121
1977	1571	1152	892	514	1058	838	722	547	345	704	638	427	280	141
1978	1909	1474	1076	607	1658	916	816	605	396	779	663	461	330	193
1979	2261	1839	1116	499	1453	853	744	488	356	666	710	480	298	177
1980	1828	1381	824	438	1131	737	635	414	306	549	594	389	229	126
1981	1519	1071	890	443	1018	715	627	436	303	569	525	371	218	118
1982	1470	1159	891	339	1070	553	441	309	260	523	487	306	159	98
1983	1481	1276	938	433	1189	771	676	465	270	559	499	294	195	118
1984	1558	1114	764	393	1069	678	558	398	247	522	472	296	167	100
1985	1653	992	688	372	1248	690	564	407	247	489	473	256	174	99
1986	1795	1235	928	426	1298	819	688	484	263	602	481	289	200	115

Table 3.18. continued.

1987	1944	1423	945	467	1510	896	740	479	279	685	493	298	209	109
1988	2213	1497	999	473	1423	851	693	449	271	658	518	285	188	107
1989	2080	1432	919	436	1343	773	605	438	286	626	509	290	197	124
1990	1681	1187	795	427	1112	674	529	401	268	607	499	287	181	122
1991	1557	1067	803	408	1152	791	669	535	273	576	508	303	173	110
1992	1788	1275	1016	603	1370	953	831	611	344	785	628	413	245	143
1993	2430	1687	1276	671	1856	1131	1010	696	406	861	657	432	296	180
1994	2287	1647	1221	746	1702	1089	959	669	399	-	742	460	296	181
1995	2075	1382	1173	535	1324	994	873	612	353	-	640	408	242	147

Sources: Western Wood Products Association. 1971-1995. Inland F.O.B. price summary.

Figure 3.6. Western white pine lumber grade composition, western U. S. mills, 1971-1995.

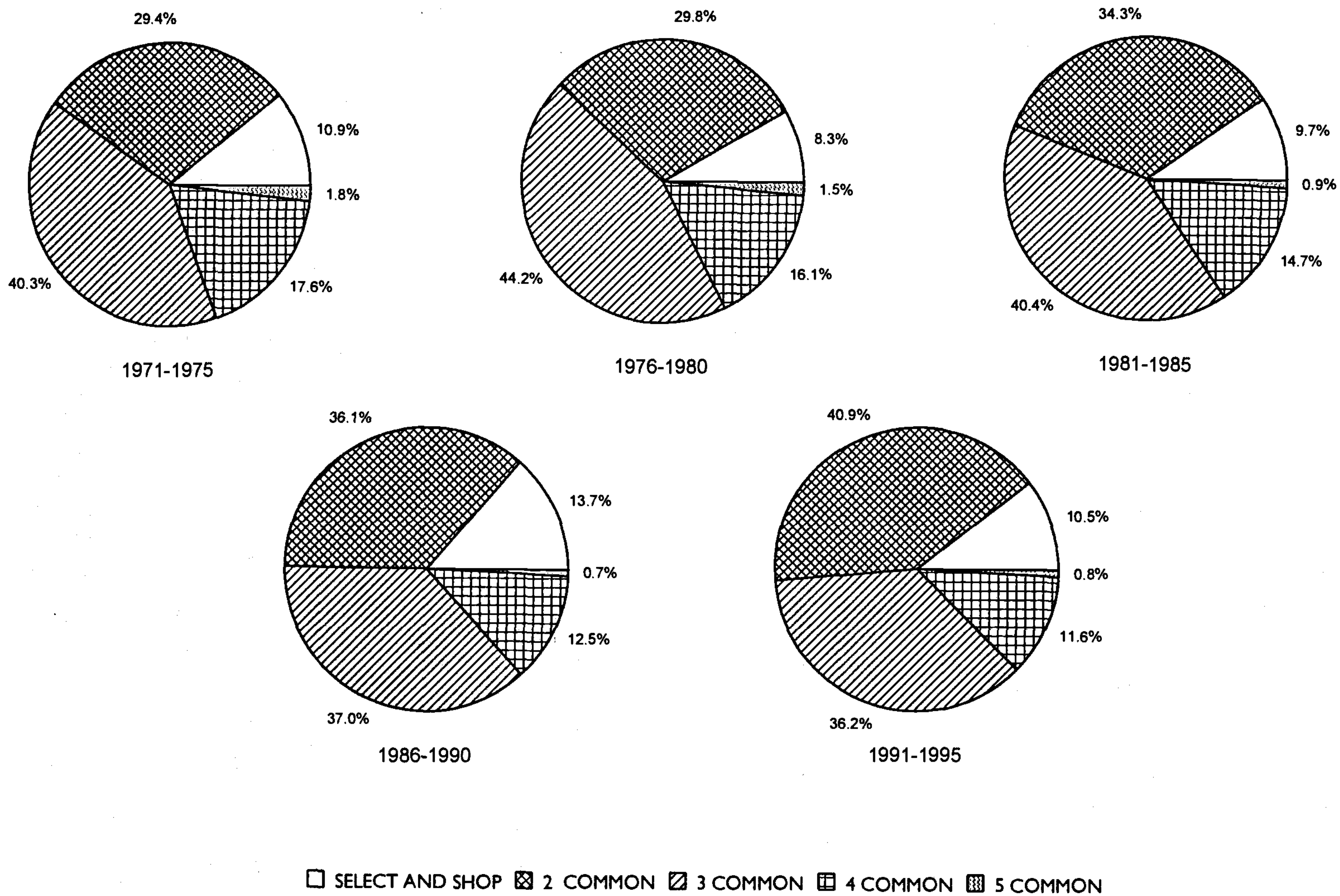
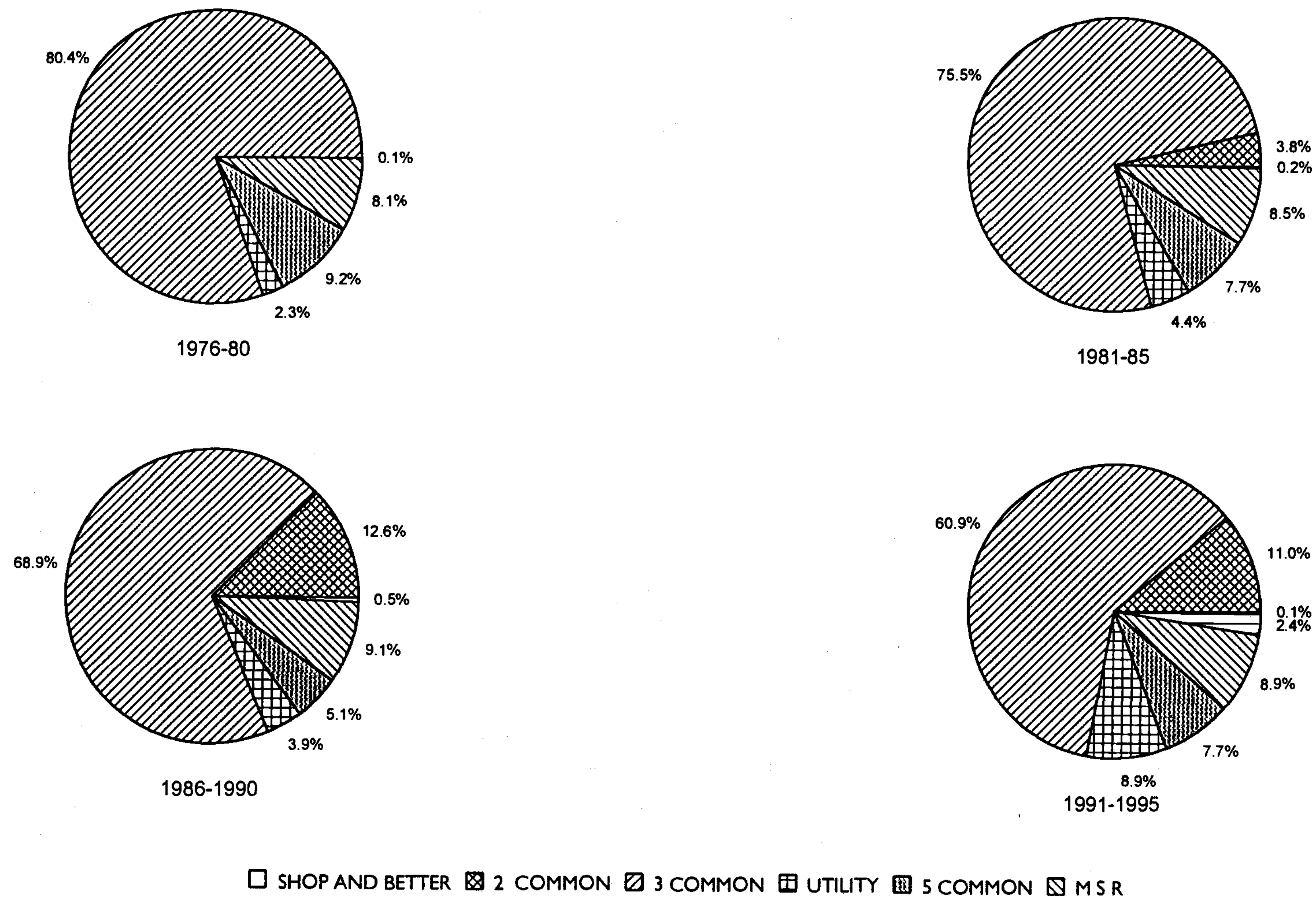


Table 3.19. Real prices for western white pine lumber, western U. S. mills, 1971-1995.

Year	D select and better	shop and better	2 common	3 common	4 common	5 common
	-------------------1990 U. S. dollars per thousand Scribner board feet-------------------					
1971	866	439	472	315	243	104
1972	948	503	572	410	312	139
1973	1128	644	743	579	419	232
1974	1222	586	770	466	282	156
1975	943	430	580	316	199	87
1976	1008	541	629	416	264	111
1977	1075	572	650	456	278	127
1978	1307	723	807	513	319	165
1979	1652	605	733	503	294	168
1980	942	450	587	351	218	114
1981	911	444	570	331	193	101
1982	957	376	571	297	154	85
1983	989	475	567	299	175	92
1984	1028	448	574	333	173	91
1985	1060	447	644	320	153	83
1986	1333	564	658	338	177	88
1987	1392	609	675	346	191	86
1988	1451	578	619	315	185	80
1989	1285	555	653	316	180	89
1990	1098	519	628	314	172	88
1991	1013	527	610	300	169	82
1992	1297	684	598	381	236	141
1993	1588	788	618	391	263	166
1994	1579	791	661	444	281	166
1995	1263	599	670	383	254	136

Sources: Western Wood Products Association. 1971-1995. Inland F.O.B. price summary.

Figure 3.7 Whitewood lumber (including lodgepole pine) grade composition, western U. S. mills, 1974-95.



3.3.6. Whitewood (Including Lodgepole Pine) Trends

This category is a catch-all for lodgepole pine, Sitka spruce, and Englemann spruce. The greatest proportion of lumber manufactured has historically been in the 3 common grade category (figure 3.7. and table 3.13.). The share of 3 common grades in lumber production has been declining since the mid-eighties as the proportion of 2 common grade category has increased. Whitewoods comprise the only lumber group that has seen a recent growth trend in the proportional importance of utility grades. During the early 1990s, small amounts of shops and better lumber were produced. Production of whitewood lumber varies cyclically, reaching peaks of production in 1977-1979 and 1987-1992.

Whitewoods are commonly considered the least valuable of the commercial softwood species. Figure 3.2. and table 3.20. show that the average value of lumber produced from whitewoods is not substantially different from the hem-fir resource in the west-side of the Pacific Northwest. Whitewood lumber has been the most irregularly tracked and deserves more study to understand its present and potential role in lumber supply from the Pacific Northwest.

3.4. Method of Analysis

The focus of this study is somewhat different from that of Haynes and Fight (1992). As in their study, regression equations are developed for aggregated lumber grades by species or species group. But, here the regressions for lumber types are related to average regional prices for lumber (table 3.1.), as compiled by the WWPA, rather than to a dominant lumber class (for example, Douglas-fir light framing as the base price series for all other Douglas-fir and hem-fir lumber grade categories). The aim here has been to

Table 3.20. Real prices for whitewood lumber (including lodgepole pine), western U. S. mills, 1974 -1995.

Year	shop and better	2 common and better	3 common and better	4 common and better	utility	5 common	MSR
	1990 U. S. dollars per thousand Scribner board feet						
1974	-	530	243	231	214	94	-
1973	-	458	259	206	219	100	-
1976	-	462	305	260	264	102	-
1977	-	-	336	260	268	120	-
1978	-	-	363	293	286	156	-
1979	-	-	336	280	253	133	-
1980	-	-	246	214	187	113	-
1981	-	-	225	184	165	101	-
1982	-	-	191	151	148	94	-
1983	-	-	243	182	198	109	-
1984	-	393	219	170	163	93	258
1985	-	384	212	143	167	90	256
1986	-	417	237	175	193	94	274
1987	-	439	237	187	196	94	284
1988	-	421	236	253	185	98	274
1989	-	382	236	250	210	103	278
1990	-	395	219	207	202	95	259
1991	-	411	235	205	204	91	277
1992	-	462	285	246	269	122	302
1993	853	502	348	304	328	164	460
1994	923	598	379	304	359	149	-
1995	847	499	285	262	269	130	373

Sources: Western Wood Products Association. 1971-1995. Inland F.O.B. price summary.

derive historical relations for use in forecasting lumber prices for the existing range of lumber grade groupings defined in this study.

The present analysis emphasizes only the commercial timber species in the Pinaceae from the Pacific Northwest west of the Cascade Crest. Timber species in the Cupressaceae (various cedars) will be treated elsewhere. Although five pine species, ponderosa, Jeffrey, western white, lodgepole, and sugar, are commercial timber species in the west-side Pacific Northwest, average annual real prices for lumber east of the Cascade Crest and in California better characterize prices for many grades of the westside pine species. East of the Cascade Crest, ponderosa pine lumber dominates the supply; accordingly, average east-side prices are often better indicators of price behavior for pine lumber grades and end uses in contrast to Douglas-fir and hem-fir lumber grades.

Lumber grade categories for the species treated in this study are based on similar end use. This approach to classification assumes that lumber prices of different grades and species have a fixed proportional relation. In general, price relations for one grade will not differ substantially from prices of similar grades within a species or comparable grades among species. Possibilities for substitution enable consumers to replace one grade for another grade or replace the same grade from a different species if prices begin to change. Substitution enables prices to equilibrate. Hem-fir lumber, for example, consists of grades derived from timber of multiple species in the genera *Abies* and *Tsuga*, all having similar physical properties.

Each lumber grade category for each species was regressed against both east-side and west-side lumber prices series to determine which series provided the better fit. Two simple equation forms were used to develop regressions that characterize the historic pattern of relation between a lumber grade category and average lumber price for a region. The first set of equations follows the form suggested for marketing margins (George and King 1971):

$$\text{grade price}_{jt} = b_{0j} + b_{1j} * \text{price}_{\text{average lumber}, t} , \quad (1)$$

where

grade price_{jt} = the Pacific Northwest coast lumber price for the j^{th} species and grade in year t;

$\text{price}_{\text{average lumber}, t}$ = the average price for all lumber products (west or east of the Cascade Crest) in year t;

b_{0j} = the estimated intercept value of the price relation for the j^{th} species and grade; and

b_{1j} = the estimated coefficient representing the response in grade price_{jt} to a given $\text{price}_{\text{average lumber}, t}$.

The other equation form is the natural log transformation of the same relationship,

$$\ln(\text{grade price}_{jt}) = b_{0j} + b_{1j} * \ln(\text{price}_{\text{average lumber}, t}) . \quad (2)$$

In many instances, the natural log transformation produced intercept b_{0j} values that were statistically significant, in contrast to intercept values in untransformed equation.

Durbin-Watson test statistics show that serial autocorrelation occurs in the majority of regressions between prices from a lumber grade category and average lumber prices. A grid-search algorithm provided corrections for autocorrelations in equations with serial autocorrelation (Hildreth and Lu 1960). Whenever the Durbin-Watson statistic fell between upper and lower bounds of statistical significance in detecting autocorrelation, an alternative test (Durbin 1970) ascertained statistical significance for autocorrelation at α=0.05. Best regressions for lumber grade categories are presented by species or species groups in tables 3.21. through 3.26. Best regressions are those equations which have a high adjusted r^2 value, a Durbin-Watson statistic close to 2.0, and a coefficient value of b_1 significant at α=0.05.

One application of these regression equations is price forecasting. This application presupposes that the past relations between the average price of a lumber grade category and the regional average price will hold in the future. Under this assumption, regressions from tables 3.21. through 3.26. serve as price projections for lumber grades for the period 1996-2020. Future average annual prices for lumber in the eastside and westside regions of the Pacific Northwest (table 3.27.) were taken from the baseline scenario of the 1993 version of the Timber Assessment Market Model (TAMM) (Adams and Haynes 1996). Price projections for each lumber category are arranged by species in tables 3.28. through 3.33.

3.5. Results and Conclusions

Projections of prices for specific lumber grades during the next 25 years have been developed. Regressions between historical relations of lumber grades to regional average prices have been extrapolated to the future using the average annual future prices for lumber in the Pacific Northwest projected by TAMM. A different pattern of price trends emerges from the model than from the pattern of actual lumber during the past 25 years.

Over the past 25 years, the composition of lumber production has changed substantively in the Pacific Northwest west of the Cascade Crest. Greatest production increases have occurred in mid-value categories, as select and shop grades have declined in overall proportion and volume of the lumber production. Best regressions based on average regional prices are for these mid-value grade categories - an indication of the preponderant share of these grades in lumber production. Two and 3 common grades in pine species fit the average lumber price series from the west-side as well. Prices for these pine grades correspond approximately to structural items and heavy framing grade prices for Douglas-fir and hem-fir in western Oregon and Washington.

Table 3.21. Regression coefficients for prices of Douglas-fir lumber from Pacific Northwest coast mills, arranged by grade category.

grade category	b_0	b_1	adjusted r^2	Durbin-Watson statistic	equation form	base price source
C select and better	2.5614 $(p(b_0=0)=.17)$	0.7598**	0.58	1.9027‡	2	west-side
D select and shop	1.3307 $(p(b_0=0)=.20)$	0.8752***	0.88	1.9113‡	2	west-side
structural items	-69.472 $(p(b_0=0)=.11)$	1.4596***	0.91	1.8117‡	1	west-side
heavy framing	-0.8955*	1.1770***	0.89	2.0716‡	2	west-side
light framing	-0.4782 $(p(b_0=0)=.19)$	1.0646***	0.97	1.5030‡	2	west-side
utility	-0.9103 $(p(b_0=0)=.17)$	1.0776***	0.90	1.5366‡	2	west-side
economy	0.8622 $(p(b_0=0)=.97)$	0.3435***	0.75	2.2266‡	1	west-side

n=25

‡ adjusted for serial autocorrelation

* significant at $p<=.10$, ** significant at $p<=.05$, *** significant at $p<=.01$

Table 3.22. Regression coefficients for prices of hem-fir lumber from Pacific Northwest coast mills, arranged by grade category.

grade category	b_0	b_1	adjusted r^2	Durbin-Watson statistic	equation form	base price source
C select and better (n=22)	305.19**	1.3356***	0.52	1.7214‡	1	west-side
D select and shop	148.01*	1.0859***	0.82	2.1384‡	1	west-side
structural items	0.3322 ($p(b_0=0)=.40$)	0.9527***	0.97	1.2418‡	2	west-side
heavy framing	19.479 ($p(b_0=0)=.21$)	1.0167***	0.95	1.2483	1	west-side
light framing	1.4211 ($p(b_0=0)=.94$)	0.8726***	0.96	1.5717‡	1	west-side
utility	-0.9025*	1.0655***	0.87	1.3456	2	west-side
economy	0.1521 ($p(b_0=0)=.91$)	0.7915***	0.70	2.1796‡	2	west-side

n=25 unless otherwise noted

* significant at $p<=.10$, ** significant at $p<=.05$, *** significant at $p<=.01$

‡ adjusted for serial autocorrelation

Table 3.23. Regression coefficients for prices of ponderosa pine lumber from western U. S. mills, arranged by grade category.

grade category	b_0	b_1	adjusted r^2	Durbin-Watson statistic	equation form	base price source
4/4 select and #1 shop						
C select and better	3.9748**	0.5712**	0.50	1.7931‡	2	east-side
D select, 12 in	2.6318 ($p(b_0=0)=.19$)	0.7729**	0.43	2.1072‡	2	east-side
C select, 4 in; D select, 6-10 in	2.9791*	0.6584**	0.44	1.8461‡	2	east-side
D select, 4 in	2.6732*	0.6454***	0.62	2.0646‡	2	east-side
#1 shop	2.3028*	0.6518***	0.28	1.5531‡	2	east-side
5/4 and thicker moulding and shop						
moulding and better	2.5356 ($p(b_0=0)=.13$)	0.7694***	0.65	1.8671‡	2	east-side
#1 shop	431.51***	1.0635***	0.82	1.7101‡	1	east-side
#2 shop	310.46 ($p(b_0=0)=.11$)	1.1650***	0.81	1.8341‡	1	east-side

Table 3.23. continued.

#3 shop	207.45*	0.7314***	0.72	2.0088‡	1	east-side
shopout	-23.946 ($p(b_0=0)=.67$)	0.8337***	0.88	1.8235‡	1	east-side
4/4 common and 8/4 standard and better						
2 common, 12 in	266.98**	0.9433***	0.57	2.3366‡	1	west-side
2 common, 4-10 in	101.74*	0.9923***	0.80	1.6739‡	1	west-side
3 common, 6-12	-1.8669 ($p(b_0=0)=.94$)	0.8001***	0.88	2.0912	1	east-side
3 common, 4 in	-1.4292 ($p(b_0=0)=.11$)	1.1473***	0.83	1.9749	2	east-side
low value						
# 3 and utility	-0.0920 ($p(b_0=0)=.91$)	0.9207***	0.82	1.5649‡	2	west-side
5 common and economy	-2.743***	1.2608***	0.80	1.3614	2	east-side

n=25
* significant at p<=.10, ** significant at p<=.05, *** significant at p<=.01, ‡ adjusted for serial autocorrelation

Table 3.24. Regression coefficients for prices of sugar pine lumber from western U. S. mills, arranged by grade category.

grade category	b_0	b_1	adjusted r^2	Durbin-Watson statistic	equation form	base price source
C select and better	3.4920**	0.6683***	0.63	1.5530‡	2	east-side
C select, 4 in; D select, 6-12 in	3.1794**	0.6656***	0.44	1.5632‡	2	east-side
D select, 4 in	2.7218*	0.6892***	0.58	2.1055‡	2	east-side
#1 shop	2.4574**	0.6438***	0.60	2.1331‡	2	west-side
5/4 and thicker moulding and shop						
moulding and better	3.4011**	0.6261***	0.59	1.9288‡	2	east-side
#1 shop	374.41**	1.1745***	0.46	2.0698‡	1	east-side
#2 shop	218.97 ($p(b_0=0)=.21$)	1.2565***	0.74	2.2060‡	1	east-side
#3 shop	149.69 ($p(b_0=0)=.13$)	0.8866***	0.70	2.1785‡	1	east-side
shopout	0.2500 ($p(b_0=0)=.84$)	0.9298***	0.82	1.6815‡	1	east-side

Table 3.24. continued.

4/4 commons and 8/4 standard and better						
2 common, 12 in (n=23)	307.79***	0.8729***	0.70	1.8329‡	1	east-side
2 common, 4-10 in	182.69**	1.2068***	0.73	1.8675‡	1	west-side
3 common, 6-12	1.0723 ($p(b_0=0)=.20$)	0.8327***	0.79	1.9966	2	west-side
3 common, 4 in	-2.3383***	1.3034***	0.87	1.4040	2	east-side
# 3 and utility						
low value						
5 common and economy	-2.6058***	1.2554***	0.79	1.5421	2	east-side

n=25
* significant at p<=.10, ** significant at p<=.05, *** significant at p<=.01, ‡ adjusted for serial autocorrelation

Table 3.25. Regression coefficients for prices of western white pine lumber from western U. S. mills, arranged by grade category.

grade category	b_0	b_1	adjusted r^2	Durbin-Watson statistic	equation form	base price source
D select and better	3.1732*	0.6512**	0.45	2.0540‡	2	east-side
shop and better	1.7788 ($p(b_0=0)=.16$)	0.7602***	0.74	2.1625‡	2	east-side
2 common	342.51***	0.7394***	0.40	1.5358‡	1	east-side
3 common	0.0157 ($p(b_0=0)=.98$)	0.9883***	0.80	1.9225	2	east-side
4 common	-1.1727***	1.1417***	0.93	1.9754	2	west-side
5 common	-4.6944***	1.5798***	0.84	1.6651	2	east-side

n=25

* significant at p<=.10, ** significant at p<=.05, *** significant at p<=.01

‡ adjusted for serial autocorrelation

Table 3.26. Regression coefficients for prices of whitewood lumber (including lodgepole pine) from U. S. western mills, arranged by grade category.

grade category	b_0	b_1	adjusted r^2	Durbin-Watson statistic	equation form	base price source
2 common	2.6568***	0.6045***	0.72	1.8185	2	west-side
3 common	67.650 ($p(b_0=0)=.11$)	0.6363***	0.79	1.8048‡	1	west-side
4 common	-0.1741 ($p(b_0=0)=.89$)	0.9375***	0.77	2.3395	2	east-side
utility	80.357 ($p(b_0=0)=.18$)	0.4731***	0.77	1.6815‡	1	west-side
5 common	-0.8731 ($p(b_0=0)=.26$)	0.9352***	0.72	1.3155	2	east-side

n=22

* significant at p<=.10, ** significant at p<=.05, *** significant at p<=.01, ‡ adjusted for serial autocorrelation

Table 3.27. Projections of average lumber prices in the U. S. Pacific Northwest from the Timber Assessment Market Model (TAMM - 1993 version, run LR 207), 1996-2020.

Year	Westside	Eastside
	-- 1990 U. S. dollars -- *--per thousand Scribner board feet--*	
1996	380.54	446.80
1997	384.58	451.56
1998	369.84	436.43
1999	371.52	437.42
2000	366.92	434.06
2001	370.93	431.37
2002	376.67	428.68
2003	378.24	430.35
2004	387.42	439.53
2005	392.30	444.41
2006	392.49	444.50
2007	387.78	439.99
2008	392.92	444.85
2009	394.57	446.88
2010	398.87	451.25
2011	408.75	460.76
2012	416.76	469.87
2013	427.68	480.03
2014	435.42	488.42
2015	432.65	485.09
2016	430.46	482.20
2017	433.09	485.46
2018	434.57	487.29
2019	437.34	489.19
2020	434.83	486.05

Source: Adams and Haynes 1996

Table 3.28. Price projections for Douglas-fir lumber, Pacific Northwest coast mills, 1996-2020.

Year	C select	D select and shop	structural items	heavy framing	light framing	utility	economy
	--------------------in 1990 U. S. dollars per thousand Scribner board feet--------------------						
1996	1183	686	486	445	346	243	131
1997	1192	692	492	450	350	246	132
1998	1158	669	470	430	336	235	127
1999	1162	672	473	432	338	237	128
2000	1151	664	466	426	333	233	126
2001	1160	671	472	432	337	236	127
2002	1174	680	480	440	343	240	129
2003	1178	682	483	442	344	241	130
2004	1199	697	496	454	353	248	133
2005	1211	704	503	461	358	251	135
2006	1211	705	503	461	358	251	135
2007	1200	697	497	455	353	248	133
2008	1212	705	504	462	358	251	135
2009	1216	708	506	464	360	252	136
2010	1226	715	513	470	364	255	137
2011	1249	730	527	484	374	262	140
2012	1268	743	539	495	381	268	143
2013	1293	760	555	510	392	275	147
2014	1310	772	566	521	400	281	150
2015	1304	767	562	517	397	279	149
2016	1299	764	559	514	395	277	148
2017	1305	768	563	518	397	279	149
2018	1309	770	565	520	399	280	149
2019	1315	775	569	524	402	282	150
2020	1309	771	565	520	399	280	149

Table 3.29. Price projections for hem-fir lumber, Pacific Northwest coast mills, 1996-2020.

Year	C select	D select and shop	structural items	heavy framing	light framing	utility	economy
	--------------------in *1990 U. S. dollars per thousand Scribner board feet* --------------------						
1996	813	561	401	406	333	228	110
1997	819	566	405	410	337	230	111
1998	799	550	390	395	324	221	108
1999	801	551	391	397	326	222	108
2000	795	546	387	393	321	219	107
2001	800	551	391	397	325	222	108
2002	808	557	397	402	330	225	109
2003	810	559	398	404	331	226	110
2004	823	569	407	413	339	232	112
2005	829	574	412	418	344	235	113
2006	829	574	413	419	344	235	113
2007	823	569	408	414	340	232	112
2008	830	575	413	419	344	236	113
2009	832	576	415	421	346	237	113
2010	838	581	419	425	349	239	114
2011	851	592	429	435	358	246	117
2012	862	601	437	443	365	251	118
2013	876	612	448	454	375	258	121
2014	887	621	455	462	382	263	123
2015	883	618	453	459	379	261	122
2016	880	615	450	457	377	260	122
2017	884	618	453	460	379	261	122
2018	886	620	455	461	381	262	122
2019	889	623	457	464	383	264	123
2020	886	620	455	462	381	263	122

Table 3.30. Price projections for ponderosa pine lumber, western U. S. mills, 1996-2020.

	4/4 selects and #1 shop					5/4 and thicker moulding and shops					4/4 commons and better				8/4 standard low value	
Year	C and better 6-12 in	D 12 in	C and btr. 4 in, D 6-10 in	D 4 in	#1 shop	Mldg. and better	#1 shop	#2 shop	#3 shop	shopout	2 com. 12 in	2com. 4-10 in	3 com., 6-12 in 8/4 dimen.	3 com., 4 in 4 com., 4-12 in	#3 and utility	5 com. and economy
	1990 U. S. dollars per thousand Scribner board feet															
1996	1737	1553	1093	744	534	1381	907	831	534	349	626	479	357	263	238	141
1997	1748	1566	1101	749	537	1392	912	837	538	353	630	483	361	266	240	143
1998	1714	1525	1076	732	526	1356	896	819	527	340	616	469	349	256	231	137
1999	1716	1528	1078	734	526	1359	397	820	527	341	617	470	350	257	232	137
2000	1709	1518	1072	730	524	1351	893	816	525	338	613	466	347	254	230	136
2001	1703	1511	1068	727	522	1344	890	813	523	336	617	470	345	253	232	135
2002	1697	1504	1064	724	520	1338	887	810	521	333	622	476	343	251	235	134
2003	1700	1508	1066	726	521	1342	889	812	522	335	624	477	344	252	236	135
2004	1721	1533	1081	736	528	1364	899	823	529	342	632	486	352	258	241	138
2005	1732	1546	1089	741	532	1375	904	828	532	347	637	491	356	261	244	140
2006	1732	1547	1089	741	532	1376	904	828	533	347	637	491	356	261	244	140
2007	1722	1534	1082	736	528	1365	899	823	529	343	633	487	352	258	242	138
2008	1733	1548	1090	742	532	1376	905	829	533	347	638	492	356	262	245	140
2009	1737	1553	1093	744	534	1381	907	831	534	349	639	493	358	263	246	141
2010	1747	1565	1100	748	537	1392	911	836	537	352	643	498	361	266	248	143

Table 3.30. continued.

2011	1768	1590	1115	759	545	1414	922	847	544	360	653	507	369	272	254	147
2012	1788	1614	1130	769	552	1436	931	858	551	368	660	515	376	279	258	150
2013	1810	1641	1146	779	559	1459	942	870	559	376	670	526	384	285	264	154
2014	1828	1663	1159	788	566	1479	951	879	565	383	678	534	391	291	269	158
2015	1821	1655	1154	784	563	1471	947	876	562	380	675	531	388	289	267	157
2016	1815	1647	1149	781	561	1465	944	872	560	378	673	529	386	287	266	155
2017	1822	1656	1154	785	563	1472	948	876	563	381	675	531	388	289	268	157
2018	1826	1660	1157	786	565	1476	950	878	564	382	677	533	390	290	268	157
2019	1830	1665	1160	788	566	1481	952	880	565	384	680	536	391	292	270	158
2020	1823	1657	1155	785	564	1474	948	877	563	381	677	533	389	290	269	157

Table 3.31. Price projections for sugar pine lumber, western U. S. mills, 1996-2020.

	4/4 selects and #1 shop				5/4 and thicker moulding and shops					4/4 commons and 8/4 standard and better				low value
Year	C and better 6-12 in	C and btr. 4 in, D 6-12 in	D 4 in	#1 shop	Mldg. and better	#1 shop	#2 shop	#3 shop	shopout	2 com. 12 in	2com. 4-10 in	3 com., 6-12 in 8/4 dimen.	3 com., 4in 4 com., 4-12 in #3 and utility	5 common economy
	1990 U. S. dollars per thousand Scribner board feet													
1996	1939	1395	1020	535	1368	899	780	546	415	698	642	411	275	157
1997	1953	1405	1027	539	1377	905	786	550	420	702	647	415	278	159
1998	1909	1374	1003	525	1348	887	767	537	406	689	629	402	266	152
1999	1912	1376	1005	527	1350	888	769	538	407	690	631	403	267	153
2000	1902	1369	1000	523	1344	884	764	535	404	687	625	399	264	151
2001	1894	1363	995	526	1339	881	761	532	401	684	630	403	262	150
2002	1886	1358	991	532	1333	878	758	530	399	682	637	408	260	149
2003	1891	1361	994	533	1337	880	760	531	400	683	639	409	261	150
2004	1918	1380	1008	541	1354	891	771	539	409	691	650	418	269	154
2005	1932	1390	1016	546	1364	896	777	544	413	696	656	422	273	156
2006	1932	1391	1016	546	1364	896	777	544	413	696	656	422	273	156
2007	1919	1381	1009	542	1355	891	772	540	409	692	651	418	269	154
2008	1933	1391	1017	546	1365	897	778	544	414	696	657	423	273	156
2009	1939	1396	1020	548	1369	899	780	546	416	698	659	424	275	157
2010	1952	1405	1027	552	1377	904	786	550	420	702	664	428	278	159

Table 3.31. continued.

2011	1979	1424	1042	560	1395	916	798	558	428	710	676	437	286	163
2012	2005	1443	1056	567	1412	926	809	566	437	718	686	444	293	167
2013	2034	1464	1071	577	1431	938	822	575	446	727	699	453	301	172
2014	2058	1481	1084	584	1447	948	833	583	454	734	708	460	308	175
2015	2048	1474	1079	581	1441	944	828	580	451	731	705	458	306	174
2016	2040	1468	1075	579	1435	941	825	577	448	729	702	456	303	173
2017	2049	1475	1080	582	1441	945	829	580	451	732	705	458	306	174
2018	2055	1478	1083	583	1445	947	831	582	453	733	707	460	307	175
2019	2060	1482	1085	585	1448	949	834	583	455	735	710	462	309	176
2020	2051	1476	1081	583	1442	945	830	581	452	732	707	460	306	174

Table 3.32. Price projections for western white pine lumber, western U. S. mills, 1996-2020.

Year	D select and better	shop and better	2 common	3 common	4 common	5 common
	1990 U. S. dollars per thousand Scribner board feet					
1996	1270	613	673	416	273	141
1997	1279	618	676	420	277	143
1998	1251	602	665	406	265	135
1999	1253	603	666	407	266	136
2000	1246	599	663	404	262	134
2001	1241	596	661	402	265	133
2002	1236	594	659	399	270	132
2003	1239	595	661	401	271	132
2004	1257	605	667	409	279	137
2005	1266	610	671	414	283	139
2006	1266	610	671	414	283	139
2007	1257	606	668	410	279	137
2008	1266	611	671	414	284	140
2009	1270	613	673	416	285	141
2010	1278	617	676	420	288	143
2011	1296	627	683	429	297	148
2012	1312	637	690	437	303	152
2013	1331	647	697	447	312	157
2014	1346	656	704	454	319	162
2015	1340	652	701	451	317	160
2016	1335	649	699	449	315	159
2017	1341	653	701	452	317	160
2018	1344	654	703	453	318	161
2019	1347	656	704	455	320	162
2020	1342	653	702	452	318	161

Table 3.33. Price projections for whitewood lumber (including lodgepole pine), western U. S. mills, 1996-2020.

Year	2 common and better	3 common and better	4 common and better	utility	5 common
	-----1990 U. S. dollars per thousand Scribner board feet-----				
1996	517	310	305	260	126
1997	520	312	308	262	127
1998	508	303	298	255	123
1999	510	304	299	256	123
2000	506	301	297	254	122
2001	509	304	295	256	122
2002	514	307	294	259	121
2003	515	308	295	259	121
2004	523	314	300	264	124
2005	527	317	304	266	125
2006	527	317	304	266	125
2007	523	314	301	264	124
2008	527	318	304	266	125
2009	529	319	305	267	126
2010	532	321	308	269	127
2011	540	328	314	274	129
2012	546	333	320	278	132
2013	555	340	326	283	134
2014	561	345	332	286	137
2015	559	343	330	285	136
2016	557	342	328	284	135
2017	559	343	330	285	136
2018	560	344	331	286	136
2019	562	346	332	287	137
2020	560	344	330	286	136

The comparatively poor explanatory power for regressions with higher grade categories indicates that those grades respond to additional factors other than average regional prices for lumber. Overall, the rate of projected price increases has been less for high-quality select and shop lumber than for mid-grade framing lumber from Douglas-fir and hem-fir species and for common grade lumber from pine species. Projections based on regressions of lumber prices indicate that Douglas-fir and sugar and ponderosa pine species will continue to have commanding premiums for high-quality wood. Real price increases on the order of eleven to sixteen percent for high-quality Douglas-fir are forecast at the end of the projection period, 2020, in comparison to real 1995 prices. Price increases for select grades for ponderosa and sugar pines are projected at lower rates of increase, between five and nine percent. The historical ranking by value of select timber prices from each species or species group remains the same throughout the forecast period; from highest to lowest, the ranking is: sugar pine, ponderosa pine, Douglas-fir, and hem-fir (tables 3.28. through 3.33.). Ranking by rate of price increase in value from highest to lowest is different: Douglas-fir, hem-fir, ponderosa pine, and sugar pine.

Hem-fir grade lumber is likely to compete best with Douglas-fir in the framing grades. Efforts to develop high-grade hem-fir would likely work only with pruning management because of the high rate of decay and defect in older trees of hem-fir species (Harmon and others 1996). Price similarity for mid-priced products on many sites could render yield and value from hemlock and true fir species equal to the value of Douglas-fir yield. This outcome is likely where Douglas-fir is at the margin of its range, for example at higher elevations or close to the Pacific coast.

At the same time, loss of higher-quality lumber supplies and steep reductions in available resources from several pine species has prompted new thinking about means to reestablish supplies from certain timber species such as western white pine and sugar pine. Prices of common grade lumber from sugar, western white, and ponderosa pine show an eleven-percent real price increase by 2020. This fact may prove to be an incentive for more intensive planting and management for pine species.

Investment in uncommon species such as sugar and western white pines will be rewarding as the price of commons grades for the soft pines remains consistently higher than the price for comparable grades of the hard pines (ponderosa and lodgepole pines) throughout the period 1996-2020. The one pine species that until now shows no great real price increase is lodgepole pine when utilized as "whitewood." These lower-valued products maintain an eight to eleven percent real price increase from 1996 to 2020. Work to improve yield by more intensive management of lodgepole pine has not taken hold in the Pacific Northwest west of the Cascade Crest in contrast to the Rocky Mountain region.

Several means to develop higher-value lumber sources through stand management are attracting interest among forest managers. Commercial thinnings from below can extend rotations of thriftily growing retention trees. Infrequent, heavy intermediate thinnings may be able to carry the cost of developing a high-quality lumber source in forests with late-seral features designed to meet other social objectives such as conservation of biological diversity. Curtis (1995) has documented that lengthening rotations for Douglas-fir maintains good growth in large, old trees retained as canopy emergents.

Pruning young trees to reduce knot size and promote clear wood growth (Hanley and others 1995) in species not conventionally pruned can add more value to smaller-diameter trees. Inclusion of high-value pine species, such as western white pine and sugar pine, as significant components of otherwise uniform stands of Douglas-fir or hem-fir species holds promise for augmenting overall stand value. Implementing advances in management (Cole and Koch 1995, Hungerford and others 1982) for pine species can forestall premature mortality through disease and infestation to realize gains in stand-level investments for lumber product quality.

Alternative sources of incomes from a stand may also come from non-timber products in the understory. These alternatives have the potential to finance young stand management for improved timber quality. As yet, options for harvesting understory vegetation or fungi with high market values are poorly known (von Hagen and others 1996). Although stand management may become more complex with multiple crops, more intensive management can make management of forest overstories for timber quality more feasible. Joint management of residual trees to develop higher-quality timber can conversely prolong understory conditions beneficial for economic yields of non-timber products. An example of latter strategy is part of research ongoing in the Winema and Umpqua National Forests to develop a high-quality timber supply and more abundant pine mushroom crops concurrently.

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3.7. Appendices

3.7.1. WWPA Lumber Grades and their Placement within the Lumber Grade Category Classification Used by the U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

The aggregate lumber grade categories used by the Pacific Northwest Research Station in reporting regional lumber prices are listed in boldface under the appropriate timber species or species group. Names of commercial lumber grades included in a given category for analysis are listed underneath the corresponding category along with the years in which the lumber grade is recorded by the WWPA.

3.7.1.1. Grade categories for Douglas-fir lumber

Note: grades in use from 1977 to 1995 are included here.

	Years Appearing in WWPA reports
C select and better (1)	
export clear	
2 in RW/L clear and better	1977-1982
2 in RW/L #3 clear and better	1983-1992
3 in RW/L clear and better	1977-1982
3 in RW/L #3 clear and better	1983-1992
4 in RW/L clear and better	1977-1982
4 in RW/L #3 clear and better	1983-1992
5 in and thicker RW/L clear and better	1977-1983
5 in and thicker #3 clear and better	1984-1992
3 in x RW/L #4 clear	1988-1992
finish	
4/4 C and better	1977-1995
4/4 C and better VG	1977-1990
5/4 and thicker C and better	1977-1995
5/4 and thicker C and better VG	1977-1990
flooring	
4/4 C and better	1977-1990
4/4 C and better VG	1977-1990

	Years Appearing in WWPA reports
C select and better (1) continued	
industrial clear	
5/4 and thicker clear and better	1977-1992
5/4 and thicker clear and better VG	1977-1990
D select and shop (2)	
finish	
4/4 D	1977-1995
5/4 and thicker D	1977-1995
5/4 and thicker D and better	1993-1995
5/4 and thicker D and better	1995
industrial clear	
5/4 and thicker D and better	1993-1995
moulding	
4/4 moulding	1993
5/4 and thicker moulding	1993, 1995
5/4 and thicker moulding and better	1993-1995
shop	
shop	1977-1995
shop VG	1977-1995
shop MG	1977-1995

3.7.1.1. Grade categories for Douglas-fir lumber (continued)

	Years Appearing in WWPA reports
Structural items (3)	
crossarm stock	
crossarm stock	1977-1995
domestic cargo west	
3 inch and thicker #2 and better	1977-1995
export common	
2 in #2 and better merch	1993
2 in #3 and better common	1993
3 in and thicker select merch	1977-1991
3 in and thicker #1 and better merch	1984-1995
3 in and thicker #2 merch	1984-1992
3 in and thicker #2 and better	1977-1982
3 in and thicker #2 and better merch	1983-1995
3 in and thicker #3	1977-1982
3 in and thicker #3 common R lst	1983-1991
3 in and thicker #3 and better common	1993-1995
laminating stock	
laminating stock 2"	1977-1980
laminating stock 2 x 6	1981-1983
laminating stock 2 x 8	1981-1983
laminating stock 2 x 10	1981-1983
2 x 4 L3 and better	1984-1995
2 x 6 L3 and better	1984-1995

	Years Appearing in WWPA reports
Structural items (3) continued	
2 x 8 L3 and better	1984-1995
2 x 10 L3 and better	1984-1995
machine stress rated	
2 x 4 1650 F MSR	1984-1986, 1995
2 x 4 1800 F and better MSR	1984-1993
2 x 6 1800 F and better MSR	1984-1993
2 x 4 2400 F and better MSR	1995
structural joist and plank	
2 x 6 select structural	1995
2 x 6 and wider select structural	1977-1994
2 x 8 select structural	1995
2 x 10 select structural	1995
2 x 12 and wider select structural	1995
2 x 6 #1 and better	1995
2 x 6 and wider #1	1977-1993
2 x 6 and wider #1 and better	1993-1994
4 x 6 #1	1988-1992
4 x 6 #1 and better	1993-1995
4 x 8 #1	1984-1992
4 x 8 #1 and better	1995
4 x 10 #1	1984-1992
4 x 10 #1 and better	1995
4 x 12 #1	1977-1983
4 x 12 and wider #1	1984-1993
4 x 12 and wider #1 and better	1993-1995

3.7.1.1. Grade categories for Douglas-fir lumber (continued)

	Years Appearing in WWPA reports
Structural items (3) continued	
4 in x RL/W #1 and better	1993-1994
4 in x RL/W #1	1993
structural light framing	
2 x 4 select structural	1977-1995
2 x 4 #1 and better	1992-1995
2 x 4 #1	1977-1995
timber, beam, stringer	
select structural	1977-1995
Heavy framing (4)	
domestic cargo west	
2 x 10 #2 and better	1977-1995
2 x 12 #2 and better	1977-1989
2 x 12 and wider #2 and better	1990-1995
structural joist and plank	
2 x 10 #2 and better	1977-1995
2 x 12 #2 and better	1977-1990
2 x 12 and wider #2 and better	1990-1995
3 in x RW/L #2 and better	1977-1995
3 x 6 #2 and better	1995
3 x 8 #2 and better	1995
3 x 10 #2 and better	1995
3 x 12 and wider #2 and better	1995
4 in x RW/L #2 and better	1977-1994
4 x 6 #2 and better	1977-1995
4 x 8 #2 and better	1977-1995

	Years Appearing in WWPA reports
Heavy framing (4) continued	
4 x 10 #2 and better	1977-1995
4 x 12 #2 and better	1977-1983
4 x 12 and wider #2 and better	1984-1995
ties	
#1 ties	1977-1994
timber, beam, stringer	
#1	1977-1993
#1 and better	1992-1995
#2	1993-1995
#2 and better	1977-1995
standard and better	1977-1993
Light framing (5)	
board, 1 in	
standard and better	1977-1994
x 4 standard and better	1995
x 6 standard and better	1995
utility	1977-1992
utility and better	1988
utility and better 4 in	1977-1992
1 x 4 utility and better	1993-1995
utility and better 6 in	1977-1992
1 x 6 utility and better	1993-1995
domestic cargo west	
2 x 4 standard and better	1977-1995
2 x 6 #2 and better	1977-1995
2 x 8 #2 and better	1977-1995

3.7.1.1. Grade categories for Douglas-fir lumber (continued)

	Years Appearing in WWPA reports
Light framing (5) continued	
light framing	
2 x 3 standard and better	1977-1995
2 x 4 standard	1977-1981, 1983
2 x 4 standard and better	1977-1995
2 x 4 utility and better	1977-1995
3 x 4 standard and better	1992
4 x 4 standard and better	1977-1995
4 x 4 utility and better	1977-1992, 1995
structural light framing	
2 x 4 #2	1977-1987, 1990, 1992, 1994
2 x 4 #2 and better	1977-1995
2 x 4 #3	1993-1995
structural joist and plank	
2 x 6 #2	1995
2 x 6 #2 and better	1977-1995
2 x 8 #2 and better	1977-1995
2 x 6 #2 structural	
4 x 4 #1	1988-1994
4 x 4 #1 and better	1993-1995
4 x 4 #2 and better	1988-1995
stud	
standard and better	1977-1993
2 x 4 construction	1984-1995
2 x 4 standard and better	1984-1995
#2 and better	1993-1994
2 x 4 #2 and better	1984-1995
2 x 6 #2 and better	1984-1995
stud grade	1977-1983
2 x 4 stud grade	1984-1995

	Years Appearing in WWPA reports
Light framing (5) continued	
2 x 6 stud grade	1984-1995
construction	1993
Utility (6)	
light framing	
2 x 3 utility and better	1984-1991
2 x 4 utility	1977-1995
4 x 4 utility	1977-1995
structural joist and plank	
2 x 6 #3	1977-1995
2 x 8 #3	1984-1995
2 x 8 and wider #3	1977-1994
2 x 10 #3	1984-1995
2 x 12 #3	1984-1991
2 x 12 an d wider #3	1990-1995
3 x 12 and wider #3	1995
4 x 6 #3	1995
4 x 8 #3	1995
4 x 10 #3	1995
4 x 12 and wider #3	1995
3 in x RW/L #3	1977-1994
4 in x RW/L #3	1977-1994
stud	
utility	1977-1995
2 x 6 #3	1993-1995
2 x 4 utility	1984-1995
timber, beam, and stringer	
#3	1984-1992
#3 and better	1984-1987, 1989-1990

3.7.1.1. Grade categories for Douglas-fir lumber (continued)

	Years Appearing in WWPA reports
Economy (7)	
board, 1 in	
x 4 economy	1993-1995
light framing	
economy	1977-1995
2 x 4 economy	1995
4 x 4 economy	1995
structural joist and plank	
economy	1977-1995
2 x 6 economy	1995
2 x 8 economy	1995
2 x 10 economy	1995
2 x 12 and wider economy	1995
4 x 6 economy	1995
4 x 12 and wider economy	1995
stud	
economy	1977-1995
2 x 4 economy	1984-1994
2 x 6 economy	1995

3.7.1.2. Grade categories for hem-fir lumber

Note: grades in use from 1977 to 1995 are included here.

	Years Appearing in WWPA reports
C select and better (1)	
finish flooring pattern	
4/4 C and better	1977-1987
5/4 and thicker C and better	1977-1992
industrial clear	
4/4 C and better	1977-1988
5/4 and thicker C and better	1977-1991
5/4 and thicker C and better VG	1977-1992
D select and shop (2)	
dimension pullout	
D and better	1977-1995
finish flooring pattern	
4/4 D	1977-1986
4/4 D and better	1984-1989, 1991-1992
5/4 and thicker D and better	1984-1995
moulding	
5/4 and thicker moulding and better	1984-1992
shop	
shop	1995
shop VG	1977-1993
shop MG	1977-1992

	Years Appearing in WWPA reports
Structural items (3)	
decking 2 in	
select decking	1992-1993
export common	
export common	1977-1983
2 x 4 #2 and better merch	1991
2 x 6 #2 and better merch	1991
2 x 10 #2 and better merch	1989
3 in and thicker #2 and better merch	1984-1994
machine stress rated	
2 x 4 1650 F MSR	1977-1993
2 x 6 1650 F MSR	1984-1993
2 x 4 1800 F and better MSR	1977-1991
2 x 6 1800 F and better MSR	1984-1993
structural joist and planks	
2 x 6 select and structural	1995
2 x 6 and wider select structural	1977-1995
structural light framing	
2 x 4 select structural	1977-1995
2 x 4 #1	1977-1991
2 x 4 #1 and better	1993-1995
timber beam stringer	
standard and better	1977-1987

3.7.1.2. Grade categories for hem-fir lumber (continued)

	Years Appearing in WWPA reports
Heavy framing (4)	
structural joist and plank	
2 x 10 #2 and better	1977-1995
2 x 12 #2 and better	1984-1989
2 x 12 and wider #2 and better	1990-1995
3 x 12 and wider #2 and better	1995
4 x 6 #2 and better	1992-1995
4 x 8 #2 and better	1992-1995
4 x 10 #2 and better	1995
4 x 12 #2 and better	1992
4 x 12 and wider #2 and better	1993-1995
4 x 6 # 3 and better	1992-1995
ties	
#1 ties	1977-1994
timber, beam, stringer	
standard and better	1977-1987, 1993, 1995
#2 and better	1984-1987, 1994-1995
#3 and better	1993-1995
Light framing (5)	
decking 2 in	
decking 2 in	1977-1990
domestic cargo west	
2 x 10 #2 and better	1977-1991
2 x 12 #2 and better	1977-1989

	Years Appearing in WWPA reports
Light framing (5) continued	
2 x 12 and wider #2 and better	1990-1991
light framing	
2 x 4 standard and better	1977-1995
2 x 4 utility and better	1977-1995
4 x 4 standard and better	1977-1995
4 x 4 utility and better	1977-1995
structural joist and plank	
#2 and better 6 in and wider	1977-1991
2 x 6 #2 and better	1977-1995
2 x 8 #2 and better	1977-1995
4 x 4 standard and better	1988-1995
structural light framing	
2 x 4 #2	1977-1985, 1987
2 x 4 #2 and better	1984-1995
4 x 4 #2 and better	1992-1995
stud	
standard and better	1977-1994
stud grade	1977-1995
2 x 4 construction	1984-1995
2 x 4 #2 and better	1995
2 x 6 #2 and better	1984-1995
2 x 4 standard and better	1984-1995
2 x 4 stud grade	1984-1995
2 x 6 stud grade	1984-1995

3.7.1.2. Grade categories for hem-fir lumber (continued)

	Years Appearing in WWPA reports
Utility (6)	
board, 1 in	
standard and better	1977-1991
utility	1977-1989
utility and better	1977-1995
domestic cargo west	
stud grade	1977-1991
light framing	
2 x 4 utility	1977-1995
4 x 4 utility	1977-1995
structural joist and plank	
2 x 6 #3	1977-1995
2 x 8 and wider #3	1977-1994
2 x 10 #3	1995
2 x 12 and wider #3	1995
stud	
utility	1977-1983
2 x 4 utility	1984-1995
timber beam stringer	
utility and better	1984, 1987
Economy (7)	
light framing	
economy	1977-1994
2 x 4 economy	1984-1995
4 x 4 economy	1992-1995
structural joist and plank	
economy	1977-1994
2 x 6 economy	1995

	Years Appearing in WWPA reports
Economy (7) continued	
2 x 8 economy	1995
2 x 10 economy	1995
2 x 12 and wider economy	1995
stud	
economy	1977-1995
2 x 4 economy	1984-1995
2 x 6 economy	1993-1995

3.7.1.3. Grade categories for ponderosa pine lumber

	Years Appearing in WWPA reports
C select and better, 6-12 in (1)	
4/4 C select and better, 6 in	1971-1991
4/4 x 6 C select and better	1992-1995
4/4 C select and better, 8 in	1971-1991
4/4 x 8 C select and better	1992-1995
4/4 C select and better, 10 in	1971-1991
4/4 C x 10 select and better	1992-1995
4/4 C select and better, 12 in	1971-1989
4/4 C select and better, 12 in and wider	1990-1991
4/4 x 12 and wider C select and better	1992-1995
4/4 C select and better RW	1971-1976
D select, 12 in (2)	
4/4 D select, 12 in	1971-1989
4/4 D select, 12 in and wider	1990-1991
4/4 x 12 and wider D select	1992-1995
C select and better, 4 in, and D select, 6-10 in (3)	
4/4 C select and better, 4 in	1971-1991
4/4 x 4 C select and better	1992-1995
4/4 D select, 6 in	1971-1991
4/4 x 6 D select	1992-1995
4/4 D select, 8 in	1971-1991
4/4 x 8 D select	1992-1995
4/4 D select, 10 in	1971-1991
4/4 x 10 D select	1992-1995
4/4 D select RW	1971-1976

	Years Appearing in WWPA reports
D Select, 4 in (4)	
4/4 moulding stock, surf and rough	1971-1991
4/4 D select, 4 in	1971-1991
4/4 x 4 D select	1992-1995
4/4 moulding and better, surf and rough	1971-1976
4/4 moulding, surf	1992-1995
4/4 #1 Shop (5)	
4/4 #3 clear	1971-1995
4/4 #1 shop	1971-1995
5/4 and thicker moulding and better (6)	
5/4 C select and better	1971-1995
5/4 moulding stock, surf	1971-1991
6/4 moulding stock, surf	1971-1991
5/4 moulding and better, surf	1971-1995
6/4 moulding and better, surf	1971-1995
5/4 moulding, surf and rough	1992-1995
6/4 moulding, surf and rough	1992-1995
5/4 moulding and better, rough	1971-1995
6/4 moulding and better, rough	1971-1995

3.7.1.3. Grade categories for ponderosa pine lumber (continued)

	Years Appearing in WWPA reports
5/4 and thicker moulding and better (6) continued	
6/4 C select and better	1971-1995
8/4 C select and better	1971-1995
5/4 D select	1971-1995
6/4 D select	1971-1991
8/4 D select	1971-1991
5/4 #1 shop (7)	
5/4 and 6/4 #3 clear	1971-1995
5/4 #1 shop	1971-1995
6/4 #1 shop	1971-1995
8/4 #1 shop	1971-1992
8/4 and thicker #1 shop	1993-1995
5/4 # 2 shop (8)	
5/4 #2 shop	1971-1995
6/4 #2 shop	1971-1995
8/4 #2 shop	1971-1992
8/4 and thicker #2 shop	1993-1995
5/4 #3 shop (9)	
5/4 #3 shop	1971-1995
6/4 #3 shop	1971-1995
8/4 #3 shop	1971-1992
8/4 and thicker #3 shop	1992-1995
stained shop	1977-1995
5/4 #2 and better common	1992-1995
6/4 #2 and better common	1971-1995

	Years Appearing in WWPA reports
Shop out (10)	
5/4 and thicker shop outs	1971-1995
5/4 #3 common	1971-1995
5/4 #3 and better common	1993-1995
6/4 #3 common	1971-1995
5/4 #4 common	1971-1995
5/4 #4 and better common	1993-1995
6/4 #4 common	1971-1995
6/4 #4 and better common	1993-1995
5/4 and thicker #5 common	1971-1995
box (includes rough)	1977-1995
6/4 #3 common, 8 in resawn	1971-1991
6/4 x 8 #3 common resawn	1992-1994
6/4 #3 common, 10 in resawn	1977-1991
6/4 x 10 #3 common resawn	1992-1994
6/4 #3 common, 12 in resawn	1971-1989
6/4 #3 common, 12 in and wider resawn	1990-1991
6/4 x 12 and wider #3 common resawn	1992
6/4 #4 common, 8 in resawn	1971-1991
6/4 x 8 #4 common resawn	1992
6/4 #4 common, 10 in resawn	1977-1991
6/4 x 10 #4 common resawn	1992

3.7.1.3. Grade categories for ponderosa pine lumber (continued)

	Years Appearing in WWPA reports
Shop out (10) continued	
6/4 #4 common, 12 in resawn	1971-1989
6/4 #4 common, 12 in and wider resawn	1990-1991
6/4 x 12 and wider #4 common resawn	1992
shop common	1992-1995
2 common, 12 in (11)	
4/4 #2 and better common, 12 in	1971-1989
4/4 #2 and better common, 12 in and wider	1990-1991
4/4 x 12 and wider #2 and better common	1992-1995
2 common, 4-10 in (12)	
4/4 #2 and better common, 4 in	1977-1991
4/4 x 4 #2 and better common	1992-1995
4/4 #2 and better common, 6 in	1977-1991
4/4 x 6 #2 and better common	1992-1995
4/4 #2 and better common, 8 in	1971-1991
4/4 x 8 #2 and better common	1992-1995

	Years Appearing in WWPA reports
2 common, 4-10 in (12) continued	
4/4 #2 and better common, 10 in	1977-1991
4/4 x 10 #2 and better common	1992-1995
4/4 #2 and better, 8 in pattern	1971-1987
4/4 #3 common, 8 in pattern	1971-1987
3 common, 6-12 in, and 8/4 dimension (13)	
4/4 #2 shop	1971-1995
4/4 #3 common, 6 in	1971-1991
4/4 x 6 #3 common	1992-1995
4/4 #3 common, 8 in	1971-1991
4/4 x 8 #3 common	1992-1995
4/4 #3 common, 10 in	1971-1991
4/4 x 10 #3 common	1992-1995
4/4 #3 common, 12 in	1971-1989
4/4 #3 common, 12 in and wider	1990-1991
4/4 x 12 and wider #3 common	1992-1995
standard and better, 4 in	1971-1991
2 x 4 standard and better	1992-1995
standard and better, 6 in	1971
standard and better, 8 in and wider	1971
#2 and better, 6 in	1971-1991

3.7.1.3. Grade categories for ponderosa pine lumber (continued)

	Years Appearing in WWPA reports
3 common, 6-12 in, and 8/4 dimension (13) continued	
2 x 6 #2 and better	1992-1995
#2 and better, 8 in and wider	1971-1976
#2 and better, 8 in	1977-1991
2 x 8 #2 and better	1992-1995
#2 and better, 10 in	1977-1991
2 x 10 #2 and better	1992-1995
#2 and better, 12 in	1977-1989
#2 and better, 12 in and wider	1990-1991
2 x 12 and wider #2 and better	1992-1995
appearance	1974-1976
standard and better studs	1971-1976
stud	1971-1976
stud grade	1977-1991
utility and better studs	1971-1976
select decking, 6 in	1977-1991
2 x 6 select decking	1992-1995
#2 and better patio	1992-1995
3 common, 4 in, and 4 common, 4-12 in (14)	
4/4 shop outs	1971-1995
4/4 #3 common, 4 in	1971-1991
4/4 x 4 #3 common	1992-1995
4/4 #4 common, 4 in	1971-1991
4/4 x 4 #4 common	1992-1995
4/4 #4 common, 6 in	1971-1991
4/4 x 6 #4 common	1992-1995

	Years Appearing in WWPA reports
3 common, 4 in, and 4 common, 4-12 in (14)	
4/4 #4 common, 8 in	1971-1991
4/4 x 8 #4 common	1992-1995
4/4 #4 common, 10 in	1971-1991
4/4 x 10 common #4 common	1992-1995
4/4 #4 common, 12 in	1971-1989
4/4 #4 common, 12 in and wider	1990-1991
4/4 x 12 and wider #4 common	1992-1995
# 3 and utility (15)	
#3	1971
#3, 6 in and wider	1972-1991
2 x 6 and wider #3	1992-1994
2 x 6 #3	1995
2 x 8 #3	1995
2 x 10 #3	1995
2 x 12 and wider #3	1995
utility	1971
utility, 4 in	1972-1991
2 x 4 utility	1992-1995
5 common and economy (16)	
4/4 #5 common	1971-1995
economy	1971-1994
2 x 4 economy	1995
2 x 6 economy	1995
2 x 8 economy	1995

3.7.1.3. Grade categories for ponderosa pine lumber (continued)

	Years Appearing in WWPA reports
5 common and economy (16) continued	
2 x 10 economy	1995
2 x 12 and wider economy	1995

3.7.1.4. Grade categories for sugar pine lumber

	Years Appearing in WWPA reports
C select and better, 6-12 in (1)	
4/4 C select and better	1977-1995
4/4 C select and better, 6 in	1971-1976
4/4 C select and better, 8 in	1971-1976
4/4 C select and better, 10 in	1971-1976
4/4 C select and better, 12 in	1971-1976
C select and better, 4 in, and D select, 6-12 in (2)	
4/4 C select and better, 4 in	1971-1976
4/4 D 12 in	1971-1976
4/4 D select	1977-1995
8/4 and thicker D select	1984-1991
4/4 D select, 6 in	1971-1976
4/4 D select, 8 in	1971-1976
4/4 D select, 10 in	1971-1976
D select, 4 in (3)	
4/4 D select, 4 in	1971-1976
4/4 moulding and better, surf	1971-1976
4/4 moulding, surf	1971-1995
4/4 moulding and better, rough	1971-1976
4/4 moulding, rough	1971-1992
4/4 #1 shop (4)	
4/4 #1 shop	1971-1995

	Years Appearing in WWPA reports
Moulding and better (5)	
5/4 C select and better	1971-1976
5/4 moulding and better, surf	1971-1976
5/4 and thicker moulding and better, surf	1993-1995
6/4 moulding and better, surf	1971-1976
5/4 moulding, surf	1971-1976
5/4 and thicker moulding, surf	1993-1995
6/4 moulding, surf	1971-1976
5/4 moulding and better, rough	1971-1995
6/4 moulding and better, rough	1971-1995
8/4 and thicker moulding, rough	1977-1992
8/4 and thicker moulding and better, rough	1978-1982
5/4 moulding, rough	1971-1992
6/4 moulding, rough	1971-1992
6/4 C select and better	1971-1976
8/4 C select and better	1971-1976
5/4 and thicker C select and better	1977-1995
5/4 D select	1971-1976
6/4 D select	1971-1976
8/4 D select	1971-1976
8/4 and thicker D select	1984-1991

3.7.1.4. Grade categories for sugar pine lumber (continued)

	Years Appearing in WWPA reports
5/4 and thicker #1 shop (6)	
5/4 #1 shop	1971-1995
6/4 #1 shop	1971-1995
8/4 #1	1971-1976
8/4 and thicker #1 shop	1977-1992
5/4 and thicker #2 shop (7)	
5/4 #2 shop	1971-1995
6/4 #2 shop	1971-1995
8/4 #2 shop	1971-1976
8/4 and thicker #2 shop	1977-1995
stained select	1984-1995
5/4 and thicker #3 shop (8)	
5/4 #3 shop	1971-1995
6/4 #3 shop	1971-1995
8/4 #3 shop	1971-1976
8/4 and thicker #3 shop	1977-1995
stained shop	1977-1995
5/4 and 6/4 #2 and better common	1971-1995
Shopout (9)	
reject shop	1977-1995
5/4 and 6/4 #3 common	1971-1995
8/4 #3 common	1971-1993
box	1977-1995
shop common	1992-1995

	Years Appearing in WWPA reports
2 common, 12 in (10)	
4/4 factory select	1971-1993
factory select	1971-1976
2 common, 4-10 in (11)	
4/4 #2 and better common	1971-1995
8/4 #2 and better common	1971-1995
3 common, 6-12 in, and 8/4 dimension (12)	
4/4 #2 shop	1971-1995
4/4 #3 common	1971-1995
standard and better, #2 and better, 4 in and wider	1988-1991, 1993-1995
3 common, 4 in, and 4 common, 4-12 in,# 3 and utility (13)	
4/4 and thicker #4 common	1971-1995
4/4 and thicker #4 and better common	1993
utility and better, #3 and better, 4 in and wider	1988-1991
utility and #3, 4 in and wider	1988-1995
5 common and economy (14)	
4/4 and thicker #5 common	1971-1995
economy	1993-1995

3.7.1.5. Grade categories for western white pine lumber

	Years Appearing in WWPA reports
D select and better (1)	
4/4 choice and better	1971-1995
4/4 choice	1977-1995
4/4 quality	1971-1995
5/4 choice and better	1971-1976
5/4 quality	1971-1976
Shop and better (2)	
4/4 moulding	1992-1995
4/4 moulding stock	1971-1991
4/4 factory	1971-1991
4/4 factory select	1992-1993
4/4 #1 shop	1971-1995
2 common (3)	
4/4 colonial	1971-1985
4/4 sterling 4 in	1971-1991
4/4 x 4 sterling	1992-1995
4/4 sterling 6 in	1971-1991
4/4 x 6 sterling	1992-1995
4/4 sterling 8 in	1971-1991
4/4 x 8 sterling	1992-1995
4/4 sterling 10 in	1971-1991
4/4 x 10 sterling	1992-1995
4/4 sterling 12 in and wider	1971-1992
4/4 x 12 and wider sterling	1992-1995
4/4 x R/W sterling	1992-1995
5/4 and thicker sterling	1971-1993

	Years Appearing in WWPA reports
3 common (4)	
4/4 standard 4 in	1971-1991
4/4 x 4 standard	1992-1995
4/4 standard 6 in	1971-1991
4/4 x 6 standard	1992-1995
4/4 standard 8 in	1971-1991
4/4 x 8 standard	1992-1995
4/4 standard 10 in	1971-1991
4/4 x 10 standard	1992-1995
4/4 standard 12 in and wider	1971-1991
4/4 x 12 and wider standard	1992-1995
4/4 x R/W standard	1992-1995
4/4 # 2 shop	1992-1995
5/4 and thicker standard	1971-1993
standard and better 4 in	1977-1983
4 common (5)	
4/4 utility 4 in	1971-1991
4/4 x 4 utility	1992-1995
4/4 utility 6 in	1971-1991
4/4 x 6 utility	1992-1995
4/4 utility 8 in	1971-1991
4/4 x 8 utility	1992-1995
4/4 utility 10 in	1971-1991
4/4 x 10 utility	1992-1995
4/4 utility 12 in and wider	1971-1991
4/4 x 12 and wider utility	1992-1995
4/4 x R/W utility	1992-1993
5/4 and thicker utility	1971-1990
utility 4 in	1977-1983

3.7.1.5. Grade categories for western white pine lumber (continued)

	Years Appearing in WWPA reports
5 common (6)	
4/4 and thicker industrial	1971-1995

3.7.1.6. Grade categories for whitewood (including lodgepole pine) lumber

	Years Appearing in WWPA reports
Shop and better (1)	
4/4 D select and better	1993-1995
4/4 D select	1993
4/4 moulding	1993
#1 shop	1993
#2 shop	1993
#3 shop	1993
2 common and better (2)	
4/4 2 and better common	1974-1977, 1984-1995
4/4 2 common	1994
5/4 and thicker 2 and better common	1993
3 common and better (3)	
4/4 3 common	1974-1995
4/4 3 and better common	1993-1995
standard and better 4 in	1974-1991
2 x 4 standard and better	1992-1995
#2 and better 6 in	1974-1991
#2 and better 8 in	1977-1991
#2 and better 8 in and wider	1974-1976
#2 and better 10 in	1977-1991
#2 and better 12 in	1977
#2 and better 12 in and wider	1990-1991
2 x 6 # 2 and better	1992-1995
2 x 8 # 2 and better	1992-1995
2 x 10 # 2 and better	1992-1995

	Years Appearing in WWPA reports
3 common and better (4) continued	
2 x 4 standard and better	1992-1995
2 x 12 and wider 2 common and better	1995
standard and better stud	1974-1976
stud	1974-1976
stud 2 x 4	1984-1987
stud 2 x 6	1984-1987
stud grade	1977-1983
2 x 3 stud grade	1988-1995
2 x 4 stud grade	1988-1995
2 x 6 stud grade	1988-1995
2 x 4 stud grade 9 ft and 10 ft	1992
2 x 6 stud grade 9 ft and 10 ft	1992
utility and better stud	1974-80
5/4 and thicker 3 common	1993
4/4 4 common	1974-1995
4/4 4 and better common	1974-1995
short common	1992-1995
Utility (5)	
utility 4 in	1974-1991
# 3 6 in	1974-1991
# 3 and better 6 in	1974-1983
# 3 8 in	1984-1991
# 3 10 in	1984-1991
# 3 12 in	1984-1991
# 3 12 in and wider	1990-1989
2 x 4 utility	1993-1995
utility and better 4 in	1974-1991

3.7.1.6. Grade categories for whitewood (including lodgepole pine) lumber (continued)

	Years Appearing in WWPA reports
Utility (5) continued	
2 x 4 utility and better	1992-1995
2 x 6 # 3	1992-1995
2 x 6 # 3 and better	1993-1995
2 x 10 # 3	1995
Economy (6)	
4/4 5 common	1974-1995
economy	1974-1994
2 x 4 economy	1995
2 x 6 economy	1995
2 x 8 economy	1995
2 x 10 economy	1995
2 x 12 and wider economy	1995
economy stud	1974-1994
2 x 4 economy stud	1995
2 x 6 economy stud	1995
MSR grades (7)	
2 x 4 1650 F MSR	1984-1993, 1995
2 x 4 1800 F and better MSR	1988-1993, 1995
2 x 6 1800 F and better MSR	1988
2 x 4 2100 F MSR	1995

3.7.2. Softwood Lumber Production Totals, Pacific Northwest Coast Mills, 1975-1995.

Year	Production
	million Scribner board feet
1975	7,025
1976	8,194
1977	8,665
1978	8,680
1979	8,248
1980	6,653
1981	6,112
1982	5,587
1983	7,755
1984	8,100
1985	7,833
1986	9,142
1987	10,058
1988	9,725
1989	9,491
1990	8,420
1991	7,547
1992	7,577
1993	6,889
1994	7,452
1995	7,001

Sources: Western Wood Products Association. 1983, 1991, 1995.
Statistical Yearbook of the Western Lumber Industry.

3.7.3. Commercial Timber Species in the Pinaceae Found in Western Oregon and Washington.

Common Name	*Scientific Name*
Pacific silver fir	*Abies amabilis* Dougl. ex Forbes
white fir	*Abies concolor* (Gord. and Glend.) Lindl.
grand fir	*Abies grandis* (Dougl.) Lindl.
Shasta red fir	*Abies magnifica* A. Murr. var. *shastensis* Lemmon
noble fir	*Abies procera* Rehd.
Englemann spruce	*Picea engelmannii* Parry ex Engelm.
Sitka spruce	*Picea sitchensis* (Bong.) Carr.
lodgepole pine	*Pinus contorta* Dougl. ex Loud.
Jeffrey pine	*Pinus jeffreyi* Grev. and Balf. in A. Murr.
sugar pine	*Pinus lambertiana* Dougl.
western white pine	*Pinus monticola* Dougl. ex D. Don
ponderosa pine	*Pinus ponderosa* Dougl. ex P. and C. Lawson
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
mountain hemlock	*Tsuga mertensiana* (Bong.) Carr.

4. MUSHROOM: A Bioeconomic Model for Agroforestry Systems with Joint Production of Pine Mushrooms and High-Quality Timber in the Southern Cascade Range

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Abstract

A computer program is presented that models joint production of agroforestry products including timber, pine mushrooms, conifer boughs, cones, and Christmas trees from stands near Diamond Lake in the Umpqua National Forest, Douglas County, Oregon. A review of environmental and financial considerations introduces the context for developing bioeconomic models as one tool for discovering new possibilities for generating income from forested ecosystems with low impacts on ecosystem processes and forest stand structure. Modular structure can facilitate adaptation to other programs or expanding the model with new subprograms. Inherent in the model are scenarios for testing the feasibility of directing vegetation management to augment production of pine mushrooms.

Keywords: *Abies magnifica* var. *shastensis*, adaptive management models, agroforestry, bioeconomic models, Cascade Range, Christmas trees, cones, decorative boughs, pine mushrooms, *Pinus monticola*, Shasta red fir, *Tricholoma magnivelare*, western white pine.

4.1. An Overview of MUSHROOM - an Integrated Bioeconomic Model for Agroforestry Production in the Southern Cascade Range

Interest in the capacity of Pacific Northwest forests to produce marketable products in addition to timber has grown among forest scientists, land managers, and the wider public. Although local or seasonal industries have existed in the Pacific Northwest for floral plants, boughs, cones, and mushrooms since the 1920's (Allen 1950), conscious management to augment production of non-timber forest products has lagged behind. Awareness of the need for management is comparatively recent as public land management agencies have registered increased harvests of diverse species of plants and fungi (Bureau of Land Management Taskforce 1993).

Information about environmental factors controlling production and about culturing techniques is scant or lacking for most species. Concerns about the conservation of non-timber resources and the appropriate level of their sustained harvest parallel the public controversies about effects of timber harvests on the long-term well-being of forest ecosystems and economies in the Pacific Northwest. Past investment in research on non-timber forest products in the region has been small compared to forest research on tree species, and timber production from the region has overshadowed non-timber forest products from the Pacific Northwest.

The lack of reliable information about non-timber forest products makes decisions about the extent and intensity of extraction risky. Without a tradition of management, precedents are few and uncertainty high. One response to uncertainty is to construct models. Building models formalizes acquisition and organization of current knowledge, identifies knowledge gaps and research needs, and provides a structure prepared to adapt future research knowledge and improve the predictive power of models.

The model presented here applies to resource development of multiple non-timber forest products in just one ecosystem: the pumice/ash deposition zone northwest of Crater Lake in the Diamond Lake Ranger District, Umpqua National Forest. While the geographic scope is limited, the multidisciplinary breadth necessary for such a model reflects the widespread need for resource specialists to contribute jointly their expertise in building models. Ecosystem models that predict outputs of multiple joint products are tools to aid land managers and their constituents in weighing demands, choices, constraints, and risks in producing and conserving forest products.

Several key considerations have prompted development of bioeconomic models for joint production of forest products. One major thrust is public interest in conservation of old trees and old-growth ecosystems. Mandates to conserve ecosystems have prompted many forest biologists and managers to consider extending the rotation length of timber trees, retaining residual old-growth trees, and shifting to uneven-aged stand management. Deferring timber harvests to retain late seral stage stand features creates, from a financial point of view, a loss of revenue for a landowner. A search for alternative management that maintains old-growth ecosystem features while offering alternative commercial products responds to broad public interest in forest management that departs from a single-product or single-goal focus.

Many cultures have developed complex systems of producing subsistence or commercial goods from forests while maintaining forest productivity and conserving both forest ecosystem processes and biological diversity. These systems, commonly called agroforestry systems, use the physical structure of the forest and multi-functional management practices to generate a portfolio of forest products, one of which is timber or firewood and include, in addition, forage, floral products, food, or medicinal plants. Von Hagen and others (1996) document the assortment of past, current, and potential goods from forests in the Pacific Northwest.

Implementing innovative production systems has been a cornerstone in international aid for rural economic development. Initiating appropriate parallel systems in forests of the Pacific Northwest, however, has been slow. High-value timber products from the region have provided economic wealth in the region for 150 years. Traditionally, only economically marginalized people have taken advantage of the non-timber forest product resources (Heckman 1951, Richards and Creasy 1996). But demand, frequently international in its scope, has created strong markets for non-timber forest products. Examples include the German floral industry which imports between 15-20 percent of its floral greens supplies from wild stocks of plants from the Pacific Northwest (Fischer 1992). Danish forests furnish decorative conifer boughs to the European Union; a principle source of boughs in Denmark since the early 1950's has been noble fir (*Abies procera* Rehd.) plantations. Only recently have public land management agencies in the Pacific Northwest begun intensifying bough culture with noble fir in its native habitat. Most notably in value of external trade, between 10 and 25 percent of pine mushrooms consumed in Japan come from the Pacific Northwest region, including British Columbia (Weigand 1997c). Yet, little is known about the culturing techniques for these prominent non-timber forest products as a means for expanding production and generating additional income from forests.

Greatest opportunities for experimenting and innovating with agroforestry systems are in forests whose timber productivity is low and where conventional timber harvests might have a long-term deleterious impact on the productivity of soils and stand regeneration. High-elevation forests in the Cascade Range have both these features. Establishing regeneration following clearcuts at high elevations in the Cascade Range has presented problems to many foresters (Halverson and Emmingham 1982). The montane Mediterranean climate constrains tree growth because most precipitation falls as snow, and drought characterizes the summer growing season.

From an economic viewpoint, southern Cascade forests have two advantages. The conifer tree species are diverse, including high value pine species: western white pine (*Pinus monticola* Dougl. ex D. Don), ponderosa pine (*P. ponderosa* Dougl. ex Laws), and sugar pine (*P. lambertiana* Dougl.). The region is known for its commercial crops of North American pine mushrooms (*Tricholoma magnivelare* (Peck) Redhead), also called American matsutake, a mycorrhizal fungus that frequently produces commercial quantities in forests with pumice, volcanic ash, or beach sand soils, all sites with low timber production.

MUSHROOM is a QBasic computer program designed to clarify decision making and exploring possibilities about choices for agroforestry management involving pine mushrooms. The program simulates ecosystem processes and scenarios for producing and pricing multiple forest goods. A description of the environmental features of the Diamond Lake pine mushroom stands are found in Weigand (1997b). Output from the model offers support for management decisions about the use of similar high-elevation stands in the southern Cascade Range west of the Cascade Crest.

In its current form, the model applies specifically to conditions found over a relatively small region. The model has modular structure, however, which allows other users to extract algorithms for application to other regions within the commercial range of pine mushrooms from northern California to northern British Columbia. Conversely, algorithms that enhance the scope or improve predictive power to this model can be added easily. For instance, tree growth models such as ORGANON (Hann and others 1995) and ZELIG (Urban 1993) could adapt useful modules from MUSHROOM.

The present version of MUSHROOM includes five tree species: *Abies amabilis* Dougl. ex Forbes, *A. magnifica* A. Murr. var. *shastensis*, *Pinus contorta* Dougl. ex Loud. var. *murryana*, *P. monticola*, and *Tsuga mertensiana* (Bong.) Carr. These species are typical of high-elevation forests in the southern Oregon Cascades above 1200 m. Other species may be added by adding species-specific equations and parameter coefficients to the model and adjusting environmental variables to agree with the ecological ranges of added species.

Some brief explanatory notes about notation are in order. Markers at ends of variable names denote variable types:

% - integer variable

& - integer with eight or more digits

! - real number with seven or less significant digits

- real number with eight or more significant digits

The following abbreviations are used widely in the documentation:

dbh tree diameter at breast height (4.5 feet or 1.37 m); and

FVS Forest Vegetation Simulator, the tree growth and yield model developed by the U.S.D.A. Forest Service.

In the source code for MUSHROOM, species have constant abbreviations: SF for Pacific silver fir, LP for lodgepole pine, WP for western white pine, RF for Shasta red fir, and MH for mountain hemlock.

The source code in its entirety is found on the diskette inserted in this thesis copy. The filename for the operational version of the source code is MUSHROOM.BAS. An ASCII version of the source code is found under the filename MUSHROOM.TXT. This second file allows for converting the QBasic text into computer software for other programming languages. A glossary of variable names used in MUSHROOM is found under the filename GLOSSARY.DOC.

In the following chapters, explanatory annotations to the source code are keyed to statement lines in the source code. Each annotation given in the source code documentation is paired with the same heading consisting of the letter "**REM**" followed by three numbers. Of the three numbers, the first indicates the chapter, the second the number of the subprogram referred, and the third, the number of the annotation remark in the subprogram. Cross-referencing permits the user to correlate computer line code to documentation explaining the origin and function of the computer code.

4.2. Documentation: the Core Program

The Core program in MUSHROOM has five functions:

- establish values for constants for use throughout the model;
- declare the component subprograms along with the variables that pass among subprograms;
- stipulate dimensions of global array variables;
- set values of variables characteristic of the forest stand being modeled; and
- direct the sequence of subroutines for executing the ecosystem processes and managerial activities involved in changing stand conditions from one year to the next.

REM 2.1.1. The core program begins by identifying global constants. Constants retain the values listed here throughout the course of the program. They are not identified in variable lists in subsequent DECLARE SUB and CALL statements. Constants also specify boundary values in the model for timber merchantability, product defect, time, stand attributes, as well as mathematical and physical constants. Other constants serve as binary signals, codes for management practices, and numerical representations for the species treated in the models.

REM 2.1.2. A series of DECLARE SUB statements lists the names of subprograms linked by the core program to direct activities. Following the name of each subroutine is a list of variables in parentheses. These variables are passed among subroutines or between the subroutine and the core program. Variables followed by parentheses in the variable lists indicate array variables. Global constants listed above are omitted from the list of variables. Contents and operations for each subroutine are described under separate headings for each subroutine in chapters 4.3. and 4.4.

REM 2.1.3. A file "STAND.OUT" is opened to receive output data from MUSHROOM. The variable **montecarlo%** tracks the number of iterations used in a Monte Carlo simulation during a simulation experiment. Each iteration consists of a 25-year simulation of stand tree growth, vegetation management, and production of timber and non-timber forest products. The number of iterations is set at 1,000 currently.

For each simulation run, the number of tree records is set at 350. Initially, each simulation has between 50 and 70 tree records of live trees. In the course of each 25-year simulation, new records of young trees are added to mimic natural regeneration or to reflect tree planting. If users wish to run the model for longer than 25 years, raising the value of the variable **maxreccount%** may be necessary.

Stand attributes include: site aspect specified in radians, elevation in hundreds of feet, metric elevation in meters, initial litter depth expressed in centimeters, site index in feet of tree growth per index time interval, and slope as a percentage of rise over run. Values for maximum basal area and maximum stand density index come from the West Cascade version of the Forest Vegetation Simulator (hereafter FVS).

The Monte Carlo simulation uses different scenarios to improve users' understanding of the implications of management choices. MUSHROOM provides twelve scenarios internal to the program that describe possible yields of pine mushroom at the Diamond Lake pine mushroom management area, four scenarios of possible trends for pine mushroom prices in the future, four scenarios for pine mushroom production in the Pacific Northwest, and two scenarios for lumber and chip prices plus extraction and manufacturing costs in the Pacific Northwest. Price scenarios are found in the subprograms MUSHROOMPRICES (section 4.4.8.) and WOODPRICES (section 4.4.16.). Scenarios for mushroom production are found in MUSHROOMYIELD (section 4.3.10.). The user specifies here which combination of scenarios are used in the simulation run.

REM 2.1.4. Array variables are redimensioned with each iteration of the Monte Carlo simulation. Dimensions of arrays are specified by an integer, an integer variable, or a variable integer plus an integer. Dimensions are expressed in parentheses following the array variable name. Arrays that contain information about individual trees have dimensions sized to the value of **maxreccount%**. Some information about trees refers to species totals. These arrays are dimensioned to the number of species treated in the program, currently set at five. Other variables, particularly those that track annual income values and quantities of products from stands, have dimensions set at **horizon% +1**, to account for the twenty-five year planning period plus year zero.

Arrays are grouped according to their dimension and listed alphabetically. Table 4.1. presents an overview of the functions of array variables in MUSHROOM.

REM 2.1.5. The values of records (**reccount%**) and the number of empty records (**freecount%**) are set to zero. The simulation begins in year zero with a designated calendar year of 1995. Generation of random numbers is mediated by the function RANDOMSHUFFLE (section 4.4.10.); the function is primed here.

REM 2.1.6. A single data file provides the input about stand tree composition and structure for an entire run. UMPQUA1.DAT is the filename storing the stand inventory used in the example here.

Table 4.1. Array variables used in MUSHROOM and the subprograms where they appear.

Array variables	*Where established*	*Where altered*
for tree records		
age%	AGES, DEATH	DEATH, TREEGROWTH
alive%	core program, CONECROPS, CULTURE	CULTURE, DEATH
barkratio!	TREEGROWTH	TREEGROWTH
crownratio!	core program, CONECROPS, CULTURE	CROWNRATIOS, LEAVES
crownwidth!	LEAVES	LEAVES
cutnumber!	CULTURE	STUMPAGEPRICING
dbh!	core program, CONECROPS, CULTURE	TREEGROWTH
ddbh!	core program	TREEGROWTH
dhgt!	core program	TREEGROWTH
empty%	core program, CONECROPS, CULTURE	DEATH
free%	DEATH	DEATH
hgt!	core program, CONECROPS, CULTURE	TREEGROWTH
lognumber!	VOLUMECALC	--
num!	core program, CONECROPS, CULTURE	CHRISTMASTREES, CULTURE, DEATH
prune%	core program, CONECROPS, CULTURE	BOUGHS
species%	core program, CONECROPS, CULTURE	--
for tree species		
boughprice!	BOUGHS	BOUGHS
decay%	LEAFLITTER	--
goal!	CULTURE	CULTURE
leaffall!	LEAVES	LEAVES
litter!	LEAFLITTER	LEAFLITTER
plant!	CULTURE	CULTURE
siteindex!	core program	--
smallnum!	CONECROPS, CULTURE	DEATH
specieslai!	LEAVES	--

Table 4.1. Continued.

for tree species continued		
targetspecies%	CULTURE	CULTURE
for accounting variables		
npv!	NETPRESENTVALUE	NETPRESENTVALUE
totboughvalue!	NETPRESENTVALUE	NETPRESENTVALUE
totconevalue!	NETPRESENTVALUE	NETPRESENTVALUE
totmushvalue!	NETPRESENTVALUE	NETPRESENTVALUE
tottimbervalue!	NETPRESENTVALUE	NETPRESENTVALUE
totxmasvalue!	NETPRESENTVALUE	NETPRESENTVALUE

Data are read into the program line by line until the cursor reading the file comes to the end of the file, that is, **EOF (1)**. A data sample is provided in Figure 4.1. The variable which represents the total tree diameter increment (**ddbh!**) is divided by ten. Data input from National Forest inventories provide diameter increments for a ten-year period. An annual increment is estimated by dividing the decadal increment by ten for use in MUSHROOM.

After each line of text is read in and decomposed into tree record variables, the variable for counting tree records is augmented by one. A tree record may contain more than or less than one tree. The variable **num!** represents the number of trees represented by a tree record. Its value is updated at least once annually as the result of mortality from increasing stand density or from management actions established in CULTURE (section 4.3.6.). Tree records also receive additional variables such as **alive%** and **empty%**, not present in the data set. These are binary variables that mark the record as a live or dead tree or a record that has no more live or dead trees.

Figure 4.1. An example of formatted data from the Umpqua National Forest, stand 214, updated to 1995 conditions.

0214001	49	RF	5.8	0.41	25.5	0.15	0	90	8
0214002	25	RF	4.5	0.31	33.0	0.15	0	90	8
0214003	35	MH	6.8	0.43	33.3	0.55	0	90	8
0214004	6	RF	16.3	2.37	86.8	0.65	0	90	8
0214005	13	RF	11.2	1.78	61.3	0.55	0	90	8
0214006	25	SF	1.5	0.10	10.0	0.15	0	90	8
0214007	20	RF	9.1	1.00	52.0	0.35	0	90	8
0214008	6	RF	16.0	1.20	84.0	0.55	0	90	8
0214009	11	MH	12.0	1.4	65.0	0.45	0	90	8
0214010	4	RF	20.6	2.40	90.0	0.45	0	90	8
0214011	25	SF	0.1	0.00	2.0	0.15	0	90	8
0214012	25	WP	2.9	0.27	13.0	0.05	0	90	8
0214013	1	RF	34.7	0.68	134.4	0.35	0	90	8
0214014	50	WP	1.0	0.20	7.0	0.45	0	90	8
0214015	225	MH	0.1	0.00	2.0	0.55	0	90	8
0214016	50	RF	1.5	0.18	11.0	0.25	0	90	8
0214017	150	LP	2.0	0.20	10.0	0.15	0	90	8
0214018	2	RF	26.9	0.91	119.7	0.35	0	90	8
0214019	50	RF	0.1	0.00	3.0	0.25	0	90	8
0214020	50	LP	0.1	0.00	3.0	0.15	0	90	8
0214021	2	MH	25.7	0.51	102.1	0.45	0	90	8
0214022	12	MH	11.8	0.68	61.0	0.45	0	90	8
0214023	24	RF	8.2	0.97	50.0	0.45	0	90	8
0214024	11	MH	12.0	0.56	59.0	0.75	0	90	8
0214025	4	RF	19.5	2.03	89.0	0.55	0	90	8
0214026	25	WP	2.2	0.42	12.0	0.55	0	90	8
0214027	8	WP	13.8	0.76	85.0	0.45	0	90	8
0214028	25	SF	0.1	0.00	3.0	0.15	0	90	8
0214029	25	RF	3.6	0.50	13.0	0.25	0	90	8
0214030	25	RF	0.1	0.00	3.0	0.25	0	90	8
0214031	25	MH	1.0	0.13	6.0	0.45	0	90	8
0214032	49	RF	5.8	0.49	25.5	0.15	0	90	8
0214033	25	RF	4.5	0.57	33.0	0.15	0	90	8
0214034	36	MH	6.8	0.35	33.3	0.55	0	90	8
0214035	6	RF	16.3	1.64	86.8	0.65	0	90	8
0214036	13	RF	11.2	1.01	61.3	0.55	0	90	8
0214037	25	SF	1.5	0.08	10.0	0.15	0	90	8
0214038	20	RF	9.1	1.00	52.0	0.35	0	90	8
0214039	7	RF	16.0	1.20	84.0	0.55	0	90	8
0214040	12	MH	12.0	1.40	65.0	0.45	0	90	8
0214041	4	RF	20.6	2.40	90.0	0.45	0	90	8
0214042	25	SF	0.1	0.00	2.0	0.15	0	90	8
0214043	25	WP	2.9	0.15	13.0	0.05	0	90	8
0214044	2	RF	34.7	1.58	134.4	0.35	0	90	8
0214045	50	WP	1.0	0.17	7.0	0.45	0	90	8
0214046	225	MH	0.1	0.00	2.0	0.55	0	90	8
0214047	50	RF	1.5	0.32	11.0	0.25	0	90	8
0214048	150	LP	2.0	0.21	10.0	0.15	0	90	8
0214049	3	RF	26.9	1.70	119.7	0.35	0	90	8
0214050	50	RF	0.1	0.00	3.0	0.25	0	90	8
0214051	50	LP	0.1	0.00	3.0	0.25	0	90	8
0214052	3	MH	25.7	0.18	102.1	0.45	0	90	8
0214053	12	MH	11.8	0.32	61.0	0.45	0	90	8
0214054	25	RF	8.2	1.08	50.0	0.45	0	90	8
0214055	12	MH	12.0	0.52	59.0	0.75	0	90	8
0214056	5	RF	19.5	2.48	89.0	0.55	0	90	8
0214057	25	WP	2.2	0.47	12.0	0.55	0	90	8

REM 2.1.7. In the initial year, when **year%** equals zero, CALL statements invoke subroutine procedures that calculate additional information about the stand and about stand management. The initial stand is assumed to have already grown for the year and undergone density-dependent mortality. The subroutine AGES (section 4.3.1.) functions only in year zero. It estimates the age of a tree at breast height (4.5 feet or 1.37 m) in year zero. In following years, TREEGROWTH (section 4.3.14.) updates the age of surviving trees with each time step used for the planning period. In this version, the time step is one year. Tree age is incremented by one year through year 25.

The order by which the core program carries out the subroutine functions is critical to the function of the entire program. STANDSTATS (section 4.3.12.), for example, must occur before TREEGROWTH so that the total number of trees per acre is determined and the amount of growing space calculated. Implicit assumptions about resource priority in the program are:

- Bough, Christmas tree, cone, mushroom, and timber harvests all occur in the autumn;
- Tree planting for stand regeneration takes place in the autumn to improve survival of small trees (Halverson and Emmingham 1982);
- Trees for timber take precedence over other uses as annual or near-annual sources of boughs, Christmas trees, and cones, and with one exception: trees marked for precommercial thinning cutting in CULTURE may be unmarked in CHRISTMASTREES (section 4.3.3.) and harvested as Christmas trees instead;
- In years when timber is harvested, pine mushroom harvests do not take place because of logistical conflict; and
- Values for stem area index, leaf area index, canopy cover, relative density, for example, remain constant during an entire year unless there is a bough sale, tree pruning, or tree cutting.

When trees are cut, planted, or pruned, STANDSTATS and LEAVES (section 4.3.9.) are called a second time in the year to calculate changes in the numbers of trees in tree records and in the canopies of pruned trees.

REM 2.1.8. The first activity in a year is tree growth. A simplified tree growth is modeled after tree growth algorithms in the West Cascades Version of the FVS (Johnson 1992, Donnelly 1995). Subprograms pertaining to tree growth provide a view into the operations of the FVS. FVS is an empirical model. Trees growth and mortality are expressed as fixed regressions based on stand density and particular species characteristics rather than as functions of environmental events and processes. Stand characteristics are calculated annually and features of the stand are modeled to change the environmental characteristics of forests that affect production of pine mushrooms. Once tree diameter and height growth are completed, CROWNRATIOS (section 4.3.5.) calculates any changes to crown width, crown length, and live crown ratio for each tree record. DEATH (section 4.3.7.) reduces the number of trees represented by a tree record based on stand density. Records for newly dead trees are established as well in DEATH.

LEAVES calculates canopy characteristics for the year. Following LEAVES, CULTURE determines management activities, both preplanned and stochastic, and sets the stage for any tree planting and cutting or human disturbance related to timber harvest. Based on management actions in CULTURE, BOUGHS (section 4.3.2.), CHRISTMASTREES, and CONECROPS (section 4.3.4.) examine the feasibility of harvests of their respective products. Feasibility depends on weather conditions specified previously in WEATHERDATA (section 4.3.16.).

Harvests for the year, if any, are calculated. STANDSTATS and LEAVES refigure stand characteristics. Timber harvest quantities are evaluated for their end products in VOLUMECALC (section 4.3.15.) and for their value in STUMPAGEPRICING (section 4.3.13.). LEAFLITTER (section 4.3.8.) models the accumulation of leaves and branch wood on the forest floor from natural needle drop, branch decay, or residue from bough and tree harvests. Mushroom yield and value are determined only if there is no timber harvest. WOODSJOBS (section 4.3.17) calculates hours of labor used in the current year to produce ecosystem products. The annual cycle ends with a call to

NETPRESENTVALUE (section 4.3.11) where harvest quantities and values of products accumulate during the 25-year planning period. At the end of successive simulations of the planning period, tallies of total harvest quantities and discounted harvest values are sent from NETPRESENTVALUE to the output file opened initially in the core program.

4.3. Documentation: First-Level Subprograms

First-level subprograms in MUSHROOM are called directly by the core program to perform their activities. There are 17 first-level subprograms in the current version of the program. Each subprogram processes data from all records of live trees and, in many instances, also data from records of dead trees. This chapter describes in greater detail the purpose of individual subprograms, the logic of the activities, the original data sources that underlie the source code, and the relations between first-level subprograms and second-level subprograms that support the purpose and function of first-level subprograms. More information on second-level programs is found in chapter 4.4.

The following sections present each of the primary subprograms, arranged in alphabetical order. Figure 4.2. displays an overview of the general operations of the primary subprograms.

4.3.1. AGES

Function - Estimate the ages of trees at breast height at the beginning of a simulation
Variables Imported: alive%, hgt!, num!, potentialheight!, reccount%, species%
Variables Exported: age%

AGES is invoked only once, in year zero, during each simulation. Live trees with heights less than breast height (4.5 ft) have an effective age of zero until they attain breast height. Beginning in year one, TREEGROWTH (section 4.3.14.) updates ages of live tree records. Dead trees also have the variable **age%** to record the number of years since death (see DEATH, section 4.3.7.). A record for small trees reaching breast height for the first time has its age incremented in the year after tree height first exceeds breast height.

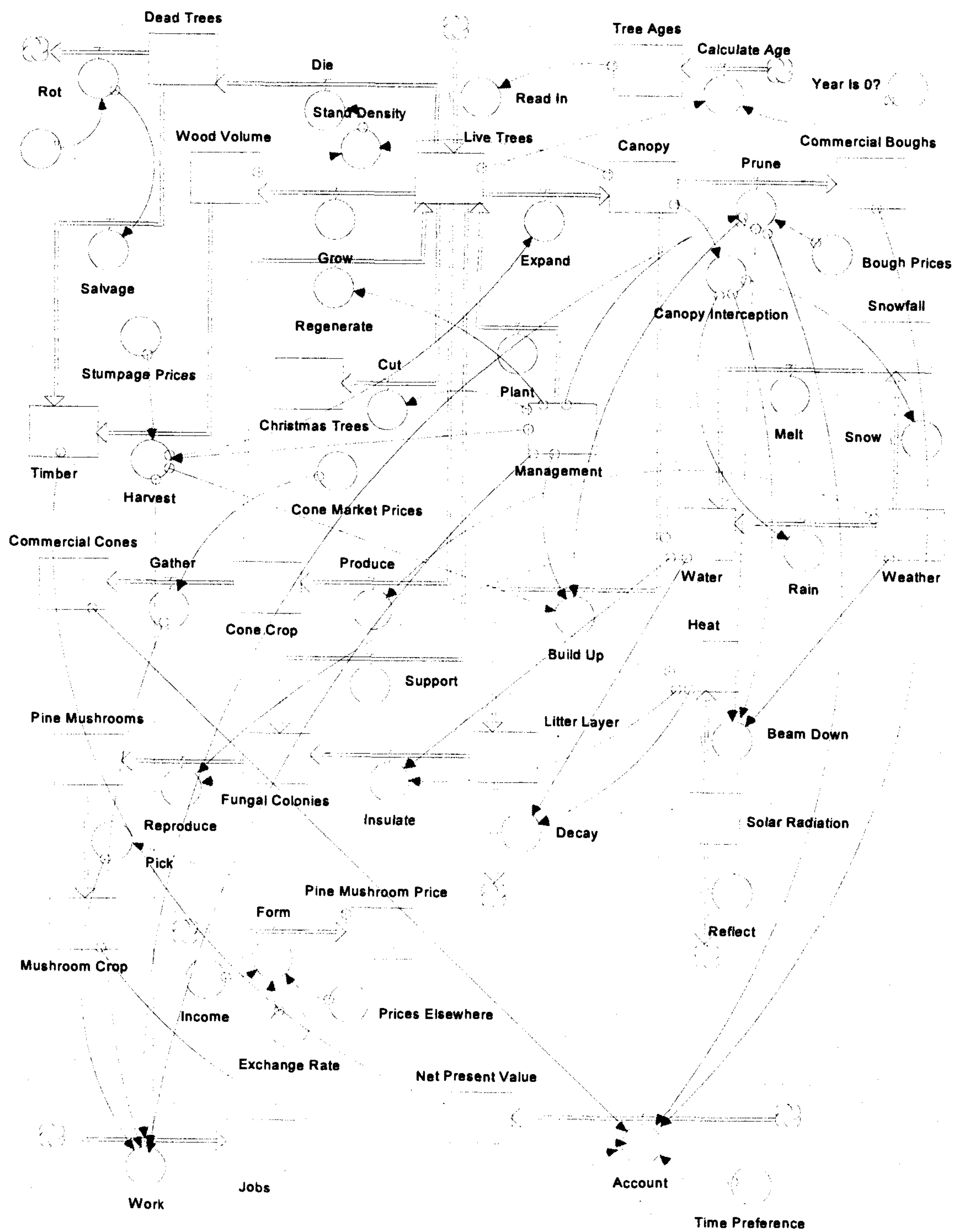
The computer code in this subprogram is adapted with modifications from the HTGF, HTCALC, and SICHG subroutines in the West Cascades variant of the FVS (Donnelly 1995).

REM 3.1.1. Species-specific site index curves estimate heights of dominant trees as functions of tree age. A site index value equals the potential height of a dominant tree of a species at a site when the tree reaches a certain age, conventionally 50 or 100 years. Site indices for tree species modeled here are established in the core program. Here, conversely, site index curves are used to estimate tree ages at year zero based on tree heights and the species-specific site index.

The subprogram first establishes a tolerance value. Iterative estimates of potential heights based on tree ages approach actual tree height. The tolerance value is the number of years within which the potential tree height must approximate the actual height. When the potential height falls within the tolerance range of the actual tree height, AGES assigns to the tree record the age that generated the close approximation of potential tree height. In the current version of MUSHROOM, the tolerance is set at ± 1 year.

REM 3.1.2. Live tree records are examined sequentially by record number up to the tree record with the highest record number. Records for dead trees, records for live trees with heights less than breast height, and inactive records (tree records without trees) are

Figure 4.2. A schematic overview of MUSHROOM using STELLA symbols.



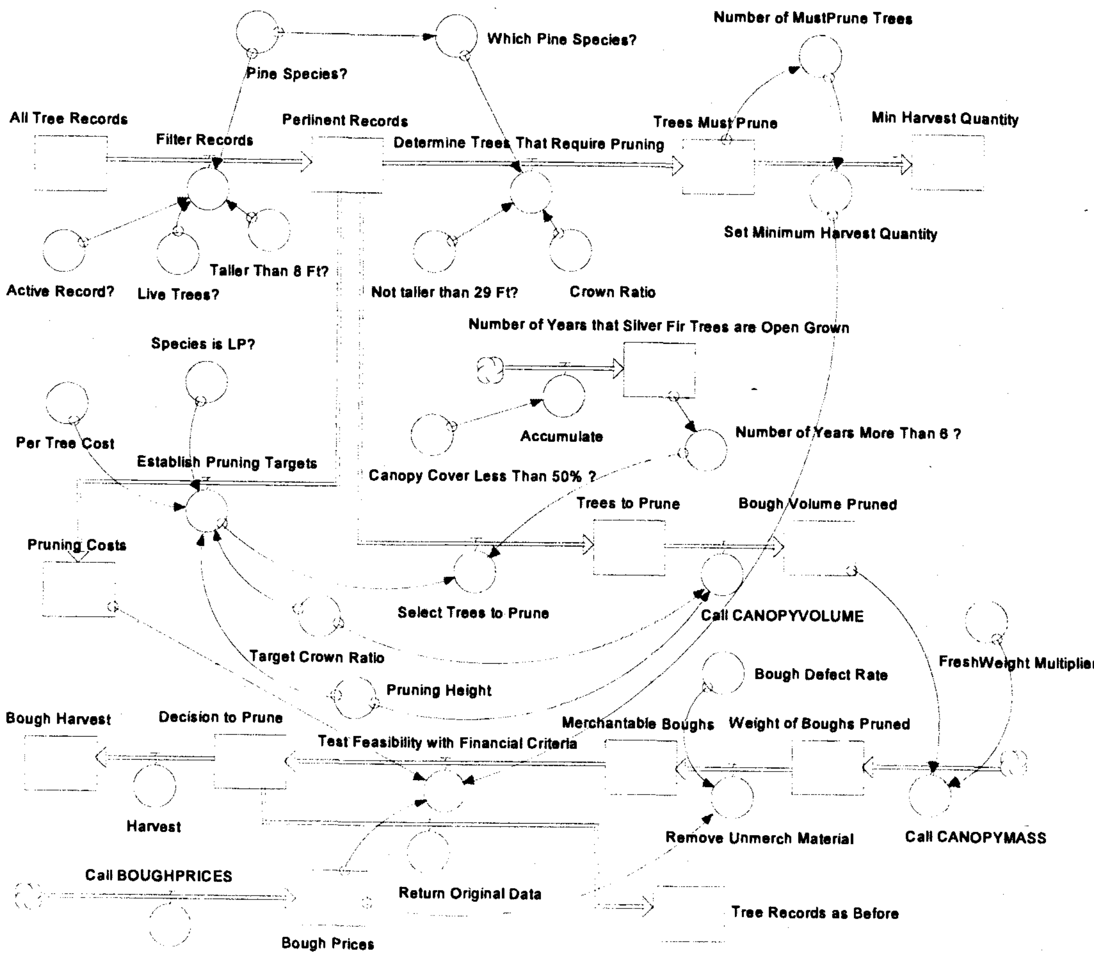
excluded from consideration. Ages of live trees less than breast height remain at zero until the trees reach breast height.

REM 3.1.3. A call to TREEHEIGHT (section 4.4.14.) returns a height value for the current tree record from the appropriate species-specific site index equation. Age for the current tree record is iteratively estimated in a comparison with successive one-year increments between the potential height of a tree at a given age at the known site index, and the actual height for the current tree record until one of two conditions is met: (1) the absolute value of the difference between the potential height and actual tree height falls within the set tolerance or (2) the height for the tree record is the largest height value that does not exceed a potential height value at a particular age. The last condition accounts for possible instances where no single height estimate from the site index curve equation falls within the set tolerance range. The age value at the conclusion of the DO LOOP sequence is the age assigned to the current record.

REM 3.1.4. For lodgepole pine tree records, the estimated tree age has five years deducted from its value. The deduction compensates for tree heights assigned to lodgepole trees in TREEHEIGHT based on the equation from Dahms (1964) for total tree age, not tree age at breast height. If the age for a lodgepole pine tree record becomes negative by deducting five years from the tree age, the tree record age is set to zero.

REM 3.1.5. In instances where the age for the tree record exceeds the maximum age allowed, the age of the tree is set to the maximum age. The maximum age is set in the core program.

Figure 4.3. A schematic overview of BOUGHS.



Pruning to the height of the small diameter end of the first, or butt, log can substantially improve the quantity and quality of wood products obtained in the butt log. Reducing knot width with timely pruning of younger trees creates more clear wood and less defect (Fight and others 1992a,b). Opportunities for salvaging ornamental boughs from whole trees marked for harvest or trees already harvested remain as yet undocumented.

This subprogram furnishes a starting point for modeling the multiple effects of pruning on stand-level production of forest goods. If there is bough pruning during a year, critical stand values such as leaf area index and canopy cover are recalculated subsequently.

REM 3.2.1. A uniform multiplier for all species is applied to dry weights estimates of foliage pruned from trees in a given year to estimate fresh bough weight. The multiplier is based on data presented by Brown (1978, table 10).

The variable **sfopenyears%** is set to zero initially and tracks the number of years that regenerating Pacific silver fir have grown in open-stand conditions. All tree records at the beginning of each simulation are assumed to have no history of pruning; **prune%** values set to zero in year zero for each tree record.

REM 3.2.2. Variables for harvest quantity and harvest value are set to zero at the beginning of the subprogram. The variables **criticalmass!** and **criticalvalue!** establish minimum thresholds for bough quantity and value on a per acre basis. A bough harvest is scheduled to occur when total boughs for commercial yield from the stand exceed the minimum critical value or volume per acre.

The variable **mustprune!** tallies the number of lodgepole and western white pines in need of pruning for disease prevention or for improving tree wood quality. *Cronartium* and *Endocronartium* spp. fungi are prevalent in the area, and trees are subject to disease if their lower branches are not pruned in a timely manner.

REM 3.2.3. The suitability of Pacific silver fir foliage for use in ornamental boughs and Christmas trees is established in this code portion. The morphology of Pacific silver fir foliage depends on light conditions around individual trees. Foliage produced in the open has lower values for specific leaf area than does foliage produced in shade (Tucker and others 1987). Foliage exposed to full sun light produces the tightly upcurved needle form preferred for commercial boughs and Christmas trees. Trees growing in low-light conditions as shade-tolerant advance regeneration require at least seven years to develop peak growth in response to changing light conditions (Tucker and others 1987). Seven years of open-grown conditions is taken as an average unbroken interval from which commercial boughs and Christmas trees might be harvested subsequently from both advance regeneration and post-harvest gap regeneration of Pacific silver fir trees.

Open-grown conditions for Pacific silver fir are defined as having less than fifty percent total overstory canopy cover, below which young trees grow well in southwest Oregon (Atzet and others 1992). A canopy cover value greater than 0.5 interrupts a previously unbroken sequence of years having suitable canopy conditions. For example, if canopy cover for open-grown foliage of Pacific silver fir is less than 0.5 in year three of the planning cycle, the foliage is considered to be grown in shade conditions. For years six and beyond, bough merchantability depends on the count of years with favorable canopy conditions being greater than or equal to seven.

Note: Shasta red fir is a less shade-tolerant species. For the purposes of modeling, Shasta red fir is assumed to always have commercial grade foliage. Shasta red fir does not grow in the Diamond Lake area as advance regeneration under closed canopies with the flattened shade foliage, characteristic of Pacific silver fir.

REM 3.2.4. A bough harvest in the Diamond Lake area requires accessible roads at times critical to bough harvesting, primarily during November. Snow pack can impede access to the site if the pack exceeds 15 cm (6 in) depth. WEATHERDATA (section 4.3.16.) determines whether criteria for accessibility are met and signals by making the binary variable **boughaccess%** positive. A bough sale proceeds only if the variable value is positive.

The local array **boughspec!** keeps a running tally of the dry weight biomass of pruned boughs for each species. The local array variable **oldprune%** is redimensioned to hold the previous value for **prune%** for a tree record as the tree record is being considered for pruning.

BOUGHS furnishes a set of species-specific bough prices. Only boughs from Shasta red fir and western white pine are assumed to have perennial markets. Demand for boughs of Pacific silver fir, lodgepole pine, and mountain hemlock is modeled to occur on average during half of all years. Markets for each of the three species are also assumed to be independent of each other.

Bough prices are based on data collected by Schlosser and Blatner (1996). All prices are expressed in constant 1990 U.S. dollars on a per pound fresh weight basis and are set at fifty percent of the value quoted by Schlosser and Blatner to approximate the value to bough pickers. Prices remain constant throughout the simulation, with one exception. After year 2010, a 25-percent increase in bough prices occurs on average in half of all years. The price increase reflects predictions of reduced bough supplies from the Pacific Northwest after 2010 (Savage 1995).

REM 3.2.5. The subprogram examines each record for live trees in the stand to see whether pruning for commercial sales or for tree vigor is feasible or necessary. Live tree records without live trees are excluded from consideration. Before examination, the variable **prunetag%** for each tree record is given a value of "no." Trees subsequently designated for pruning receive a "yes" value for **prunetag%**.

Tree height class determines suitability for bough pruning. Trees eligible for pruning must be taller than eight feet to receive an initial pruning to a four-foot height. Three classes are established: trees with heights between 8 and 18 ft, trees between 18 and 29 ft, and trees greater than 29 ft. Each height class has a target crown ratio designated as a minimum needed to preserve tree vigor after lower tree boughs have been lopped. The largest tree height class aims for a crown ratio of 0.4; the other classes have a target crown ratio of 0.5 after bough pruning. Heights are designed principally with western white pine trees in mind early in their rotation to prevent blister rust invasion of lower branches (Hagel 1989, Russell 1995). Lodgepole pines are considered for pruning in mixed-species stands only if individual trees have a crown ratio greater than 0.75. Higher standards for lodgepole pine are designed to maintain tree vigor when lodgepole pine trees is a minor component in mixed-species stands with more shade-tolerant species.

REM 3.2.6. Tree records are examined to see whether their current crown ratio retains enough crown length to prune to the appropriate four-foot, nine-foot, or 17.5-foot height. The variable **prune%** contains the number of times that a tree record has been pruned previously. If a tree has been pruned more that the maximum number of times allowed for its tree height, as specified by the variable **maxprune%**, the record is excluded from any further pruning in that tree height category.

All species except lodgepole pine have tree canopies modeled as cones; lodgepole pines have cylindrical canopies (Oliver and Larson 1990). The volume of boughs removed from a single tree is calculated from the current canopy volume based on current crown ratio and crown length and the future canopy volume with the target crown ratio and crown length reduced by the new height to crown created by pruning. The ratio between the two volumes is calculated. A call to CANOPYMASS (section 4.4.3.) provides an allometric estimate of the dry leaf mass of a tree based on the dbh alone or based on both the dbh and height of a tree. The ratio of crown volumes before and after pruning provides an estimate of bough mass removed from a single tree. The estimated mass of boughs removed from trees represented in a tree record is added to the value of **boughspec!** for the appropriate tree species.

REM 3.2.7. Labor costs of pruning figured on a per-tree basis are taken from O'Hara and others (1995a) for pruning costs for ponderosa pine, lodgepole pine, and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) in Idaho. Pruning costs increase non-linearly with the length of the crown removed. Also, differences exist among species. Per tree costs are expressed in constant 1990 U.S. dollars and are extrapolated to other species modeled here. Pacific silver fir, Shasta red fir, and mountain hemlock are assumed to have the same per-tree pruning cost as Douglas-fir. Western white pine costs are based on average pruning costs for ponderosa pine.

If pine trees from a tree record have crown ratios exceeding 0.50 (or 0.75 for lodgepole pines in mixed-species stands) and the height to crown base is less than 17.5 feet, they require pruning to resist fungal pathogens. The variable **mustprune!** totals the number of pine trees in a given year that require pruning.

Trees which meet criteria for bough pruning in a certain category are tagged with a "yes" value for **prunetag%**, and the **prune%** variable for each tree record meeting criteria is incremented. Trees that have been pruned to a four-foot height have **prune%** equal to one, an eight-foot height gives a value of two, and pruning to a 17.5-ft height brings the maximum value of three. For example, if a previously unpruned tree is then pruned to eight feet, the value of **prune%** increases from zero to two. A tree with a value for **prune%** at three indicates that the tree has already been pruned to a 17.5-foot height desired for high-quality timber in the butt log. Pruning above 17.5 feet is not considered in MUSHROOM.

A running tally of bough pruning costs adds the product per-tree pruning cost times the number of trees represented in the record for each tree.

REM 3.2.8. If more than 100 pine trees per acre are found to need a sanitation pruning, threshold bough weight and value criteria are both set back to zero.

If Pacific silver fir boughs in the stand are evaluated as unmerchantable, they have no value even when there is a market price for Pacific silver fir boughs. Unmerchantable boughs may still be cut if they have no value, in cases where the net value or net merchantable volume is still greater than the **criticalvalue!** or **criticalmass!**. A bough sale may proceed, for example, if there are a large number of pines that require pruning in a single year. The cost of bough pruning may exceed crop value when the bough mass for sanitation pruning is high.

Weights of commercial-grade foliage for a single species are calculated by multiplying together the dry-weight foliage, the fresh-weight multiplier, and the decimal fraction for boughs not considered defective. Totals for individual species are added together to give the total commercial bough mass from the stand for the current year.

Total product value is calculated similarly: multiplying commercial bough mass for each species by the respective species bough price and summing the species values together. The total cost of tree pruning is then deducted from the gross value of boughs to give the net product value. If the bough volume or bough value meet or exceed the critical volume and value thresholds, bough pruning proceeds. The variable **pruning%** is set to "yes" and signals LEAVES (section 4.3.9.) to adjust tree crown ratios and crown widths of tree records holding a positive value for **prunetag%** .

If both the bough mass and bough value are not greater than baseline criteria, commercial boughs are not sold and trees are not pruned. Total bough value, commercial bough mass, and costs incurred are set to zero. Pre-bough sale values of **prune%**, temporarily held in **oldprune%**, and "no" values for **prunetag%** are restored to individual tree records.

4.3.3. CHRISTMASTREES

Function - Determine the feasibility of a Christmas tree sale from small, naturally regenerated trees

Model ecological effects and financial benefits from Christmas tree sales

Variables Imported: alive%, crownratio!, dbh!, hgt!, num!, prune%, reccount%, sfopenyears%, species%, targetspecies%, xmasaccess%, year%

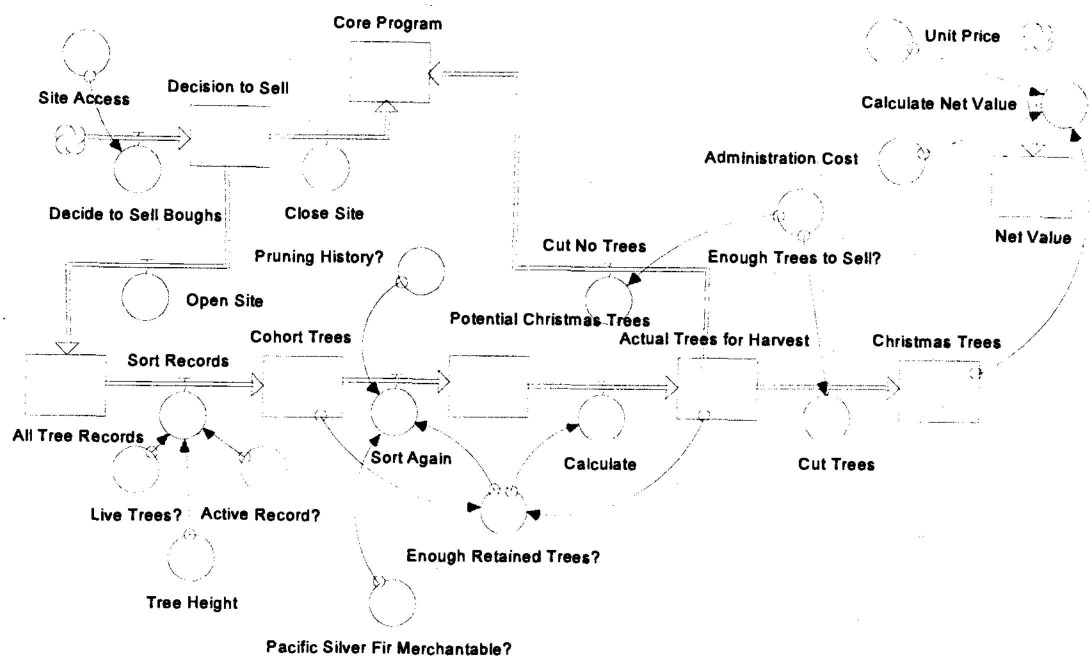
Variables Exported: cutnumber!, num!, totalcrop!, xmasvalue!

This subprogram analyzes stand conditions to test the feasibility of Christmas tree harvests. Christmas tree harvests may help to offset costs of thinning small trees for density control. Marketing Christmas trees may be difficult in the Diamond Lake area, however. Travel costs may be prohibitive and access uncertain because of weather. Product quantities and demand for species are uncertain. In areas with especially good regeneration of Shasta red fir and open-grown Pacific silver fir, however, Christmas tree harvests may be a convenient way to reduce competition among young trees and may permit greater branch extension for commercial bough harvests from other small trees retained in the stand. Reducing stand density concentrates stand growth on fewer trees from a tree cohort under uneven-aged stand management.

REM 3.3.1. A local array variable **treetag%** tags records of fir trees as suitable for harvesting as Christmas trees. Values of variables specific to the function of this subprogram are set to zero. Explanations of their meaning and function follow below.

REM 3.3.2. Weather is a major factor in feasibility of Christmas tree harvests. Snowfall could impede access during the relatively short harvest season for Christmas trees. WEATHERDATA (section 4.3.16.) exports information about site accessibility for use by CHRISTMASTREES. Information on the criteria to determine road accessibility is found under WEATHERDATA. A "yes" value means that weather conditions permit a

Figure 4.4. A schematic overview of CHRISTMASTREES



sufficient number of days free of a snowpack height that would otherwise restrict road access and entry into stands. The Diamond Lake area can offer Christmas tree harvests from mid-November and early December. If access is negative, the subprogram concludes without examining stand conditions.

REM 3.3.3. Even if there is sufficient accessibility, the absence of the necessary number of crop trees per acre prevents any commercial harvest. One criterion is that trees have sufficient crown length, that is, crowns greater than five feet long. All records of live trees are examined to see whether the criterion for crown length is met. In addition, availability of young open-grown Pacific silver fir trees may be critical to producing enough trees for a commercial crop of Christmas trees. The subprogram BOUGHS (section 4.3.2.) furnishes information about the marketability of young Pacific silver firs based on stand openness. In addition, fir trees with previous bole pruning are not considered as Christmas trees. In the model, suitable Christmas trees must be between six and ten feet tall.

REM 3.3.4. A running tally of young Pacific silver fir trees and Shasta red fir trees records the number of potential crop trees and the number of trees in the particular age or dbh cohort for each species. All trees falling within the merchantable height class are cohort trees, but only trees without previous pruning or grown in open stands are included as crop trees.

REM 3.3.5. If eligible trees from tagged records have been previously designated in CULTURE (section 4.3.6.) for cutting in the current year, they are automatically added to the total of crop trees and removed from the list of trees to be cut as part of a pre-commercial thinning.

REM 3.3.6. The number of crop trees from the two species is summed. If there are less than fifty crops trees, no sale is planned. If there are enough crop trees, additional criteria must be met. Based on management information from CULTURE, one or both of the fir species may be targeted for stand regeneration in gaps created from single-tree or group selection cuts. Designation of target species is passed to CHRISTMASTREES with the array variable **targetspecies%**.

When either species is targeted for regeneration in gaps, it is important to know whether enough trees of the size to be Christmas trees will remain after harvest to satisfy regeneration needs. In the current version, a cohort of at least 32 Pacific silver fir or 32 Shasta red fir trees per acre in the merchantable height class for Christmas trees must remain to meet regeneration needs. If less than 32 trees remain, trees are deducted from the crop tree total to make up for required cohort composition. A tally of the number of trees deducted from the crop tree total to compensate the cohort total is held by the variable **difference!**. The variables **sfdeductratio!** and **rfdeductratio!** designate the ratio between the number of needed cohort trees and the total number of trees initially designated as crop trees.

REM 3.3.7. Crop trees are counted again. If the count of total crop trees remains greater than or equal to 50 trees per acre, a Christmas tree sale takes place. In the current version, the sale value of a Christmas tree is $1.82, the amount paid on average for Shasta red fir Christmas trees from National Forests in Oregon for calendar year 1996. The price is expressed in constant 1990 U.S. dollars. The cost of sales administration is fixed at $7.00 per acre.

REM 3.3.8. Trees tagged as sale trees have their pre-sale number of trees stored in the variable **oldnum!**. The number of trees remaining in the stand is the old number less the number of trees cut. Sale trees and any trees previously marked for cutting from the same tree record are combined in the variable **cutnumber!** and all cut trees for that record are considered merchantable. If there is no deduction, all trees represented by the record are harvested and the tree has a value for **num!** equal to zero.

An accounting tally of the value of Christmas trees sums income value as records are reviewed in a final pass. If less than 50 trees per acre are suitable as Christmas trees, a sale is deferred and product value is zero for the year.

4.3.4. CONECROPS

Function - Calculate the numbers of cone-bearing trees, cones, and seeds per acre for each tree species

Model natural regeneration in canopy gaps

Determine whether a commercial harvest of pine cones is feasible

Calculate the value of commercial crops of pine cones for ornamental uses

Variables Imported:	age%, alive%, canopycover!, dbh!, functionnumber%, hgt!, lastentry%, normal!, num!, reccount%, species%, year%
Variables Passed:	alpha!, beta!, betamultiplier!, key1!, key2!
Variables Exported:	age%, alive%, conevalue!, crownratio!, dbh!, empty%, hgt!, lpconesperacre!, lpharvestrate!, smallnum!, species%, num!, wpconesperacre!, wpharvestrate!

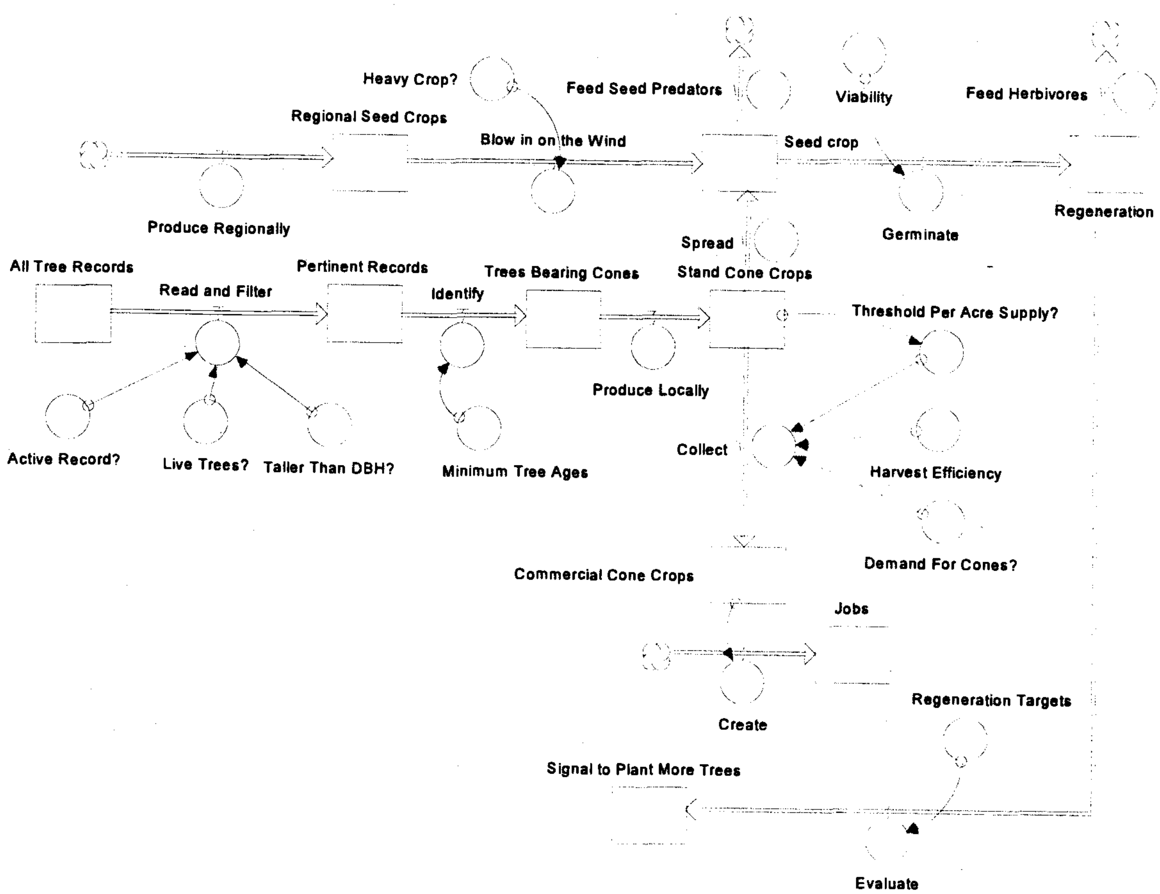
CONECROPS is called once a year to project natural regeneration. Natural seeding from cone crops is an inexpensive way for regenerating stands, particularly when an adequate overstory provides seed from desirable species and microsite conditions are favorable to seed germination and early tree growth. Harsh sites and infertile soils make natural regeneration slow at high elevations in the Diamond Lake area. Several years of moderate to excellent cone crops may be needed to successfully regenerate gaps created from timber harvests.

This subprogram passes information to CULTURE (section 4.3.6) about species populations to aid in ascertaining the success of natural regeneration. The second major function of this subprogram determines whether cone production in a given year is large enough to support an economic harvest of decorative pine cones. Two species that are commercially important in the Pacific Northwest are covered in the model: lodgepole pine and western white pine (Thomas and Schumann 1993).

REM 3.4.1. With each call to CONECROPS, multiple species-specific array variables are redimensioned with initial zero values. The variable **conetrees!** tracks the number of cone-bearing trees in the stand contributing to the total cone and seed production for a species in one year. Other array variables tally estimates of numbers of cones per tree,

cones per acre, seeds per cone, and seeds per acre. The array variable **fit%** describes the suitability of stand conditions for germination of individual species.

Figure 4.5. A schematic overview of CONECROPS.



Note: Seed banks in the soil are not modeled in MUSHROOM. Seed viability is assumed to last just one year.

REM 3.4.2. Records of live trees taller than breast height are examined to tally the number of trees which qualify as cone-producing trees or, in the case of lodgepole pine, to tally the number of cones per acre. Species-specific estimates of cone trees depend on the age, the dbh class, or tree height (Young and Young 1992).

For lodgepole pine, trees are sorted by three dbh classes (Lotan and Critchfield 1990, Koch 1987): 1- 4.5 in dbh, 4.5 - 7.5 in dbh, and greater than 7.5 in dbh. Each tree from a dbh class is modeled as having a fixed number of cones per species. For western white pine, all trees greater than ten feet high and older than ten years at dbh are considered mature cone-bearing trees (Franklin 1968). Age limits apply to the hem-fir species (Young and Young 1992).

REM 3.4.3. A random number determines the particular regional pattern of cone crops for Pacific silver fir, western white pine, Shasta red fir, and mountain hemlock. Ratings for species-specific cone crops are based on linked cone crop occurrence patterns reported by Franklin and others (1974) for collection sites in the southern Oregon Cascades between 1962 and 1972. Data for mountain hemlock, Shasta red fir, and western white pine come from sites at Windigo Pass, Diamond Lake Ranger District, and Bessie Rock, Prospect Ranger District. Data for Pacific silver fir come the most southerly site reporting Pacific silver fir, Wildcat Mountain in the Willamette National Forest. Lodgepole pine was not among the species included in the study.

The linked frequencies in the time series documented by Franklin and others (1974) show, for example, that all four species simultaneously have virtual cone crop failures roughly once in three years. In nine percent of all years, all species simultaneously have bumper crops. Average cone counts per tree for each study are represented by the variable **conespertree&**.

REM 3.4.4. Data on the number of seeds per cone by species come from the Young and Young (1992). Numbers of seeds generated per species per acre are the product of the number of cone trees per acre times the estimated number of cones per tree times the estimate of the number of seeds per cone.

REM 3.4.5. An historical record of cone prices from the Pacific Northwest does not exist. The subprogram makes the following assumptions about commercial cone prices:

- real prices in constant 1990 US dollars for lodgepole and western white pine cones remain constant over time;
- lodgepole cones are $0.01 apiece and western white pine cones are $0.05 apiece;
- twenty-five percent of the total lodgepole pine cone crop is commercially harvested in any given year with a commercial crop; and
- forty-five percent of the total western white pine cone crop is harvested in a given commercial crop year.

The lower harvest recovery for lodgepole pines reflects the fact that the cones are smaller and more likely to be overlooked by commercial gatherers. Economic crops of pine cones will be most lucrative where the density of pine species is highest and when there is an abundant crop year. Many of the sites where pines grow in the Diamond Lake area are level and easily accessible to gatherers. Prices for lodgepole pine and western pine cones are based on Thomas and Schumann (1993) in the Rogue River National Forest, south of Diamond Lake.

Value of an annual cone crop for the Diamond Lake area is calculated as the product of harvest rate times cone price times cones estimated per acre. For economic harvests, the per acre value of cone crops must exceed US$200, figured in 1990 dollars.

REM 3.4.6. A qualitative measure of site suitability or "fitness" of a species to regenerate in the stand is based on the gap space and the type of past stand disturbance (Minore 1979). One minus the percent current canopy cover in the stand is characterized as the portion of the stand in gap space. The pine species respond most positively to large gaps (Halverson and Emmingham 1982) whereas shade-tolerant species, such as mountain hemlock and Pacific silver fir, are favored in stands with small gap space. Disturbance history is also taken into account. Lodgepole pine is modeled to respond best in the aftermath of fire disturbance whereas the shade-tolerant species are favored in stands without soil disturbances, fire, or logging.

REM 3.4.7. In years of heavy or very heavy seed crops, the composition of cone-bearing trees in a stand may not completely represent the annual input of seeds to the stand. A stochastic model adds a contribution from seeds of species not presently in the stand. High numbers of seeds are based on the number of cones per tree as determined from the cones per tree values for species determined in REM 3.4.3.

REM 3.4.8. CONECROPS generates populations of young trees and stores data about the populations of the young trees in the array variable **smallnum!**. When trees reach the actual age of four, in contrast to the age at breast height determined in AGES (section 4.3.1.), a new record is generated for each species with a surviving contribution of small trees. Young trees adopt a stochastically determined crown ratio based on an algorithm in the West Cascades version of the FVS.

With each call to CONECROPS, the age of a species cohort of trees younger than four years old is advanced by one year.

REM 3.4.9. Germination rates of tree species are based on triangular distributions adapted from data about minimum, maximum, and average rates of seed germination (Young and Young 1992). A random value for germination rate is selected for each species in each year. In addition, deduction from the seed supply comes from a seed herbivory rate. Seedling mortality for non-competitive sources such as microclimate and grazing during the first four years also reduce the final number of surviving tree seedling. Each rate is species-specific.

Note: Density-dependent mortality on young seedlings is calculated in DEATH (section 4.3.7.).

REM 3.4.10. Before closing, the subprogram converts amounts of annual stocks of pine cones per acre to new variables. These variables are exported to WOODSJOBS (section 4.3.17.).

4.3.5. CROWNRATIOS

Function - Estimate new crown ratios for each tree record each year

Variables Imported: alive%, crownratio!, dbh!, dhgt!, hgt!, num!, qmd!, reccount%, relden!, species%, tpatot!, year%

Variables Exported: crownratio!

CROWNCHANGE is called once each year after year zero. This subroutine is based on the FVS subroutine CROWN.FOR. Dixon (1985) describes the theory and method of computing changes in crown ratios of trees used in FVS, and Donnelly (1995) provides a concise overview of the FVS routine used in the West Cascades and Pacific North Coast model variants.

REM 3.5.1. The local array variable **rank%** is redimensioned with each call to CROWNCHANGE. It automatically assigns initial zero values to each array element.

REM 3.5.2. All tree records are examined in this subprogram and assigned a rank in ascending order of dbh. Tree records with the largest rankings have the largest dbh's. Dead tree records, live tree records that no longer contain trees, or records for trees shorter than breast height are all assigned an arbitrarily high rank of 2,000. A counter variable **count%** begins at zero to keep a running total of the number of tree records that are assigned 2,000 as a rank.

REM 3.5.3. When a tree record represents live trees and tree height is above breast height, the record contributes to raising the maximum rank possible for tree records arranged in ascending order by height. Any excluded records, represented by the variable **count%,** keep the value of the maximum rank less than the number of total tree records in the program data set.

REM 3.5.4. Previously searched records may be reordered by rank as the current record is being processed. As long as the value of the difference is positive between the dbh for the current record and a record already assigned a rank, the counter **numeral%** continues to increase. The counter **numeral%** determines the final rank of the current tree record in the current cycle.

REM 3.5.5. Should two different records have the same dbh value (that is, their difference is zero), they share the same rank. If the dbh of the current record is the largest dbh of the records examined thus far (that is, the value of **cycle%** equals the value of **record%** and the record has previously not been ranked in the current year), the tree record then holds the current value of **maxrank%**.

REM 3.5.6. If the dbh of the current record is no longer the largest dbh in the rankings, the value of variable **difference!** becomes negative. If **difference!** is equal to the lowest negative value thus far, **mindifference!**, it is fit into the ascending rank of dbh's at the rank where it is no longer larger than the next higher-ranked record. All tree records with dbh's larger than that of the current record have their rank increased by one.

REM 3.5.7. A new stand density index is calculated as the product of the total number of trees per acre times one-tenth the quadratic mean diameter raised to the power 1.605. The equation here is adapted from Reinecke's (1933) equation to predict the number of trees per acre as a function of the quadratic mean diameter with two parameters for even-aged, monospecific stands. The equation is rearranged to estimate stand density index:

$$StandDensityIndex = TreesPerAcre * (QMD/10)^{1.605}.$$

REM 3.5.8. Crown ratios are assigned to tree records using a Weibull probability density function. Species-specific parameters values, including a Weibull "a" parameter, are selected for each record representing live trees greater than breast height. A relative stand density index common to all five species is computed from the quotient of the new stand density index and the maximum stand density index for a given index. The maximum density index is set previously in the core program based on the *Tsuga mertensiana / Vaccinium scoparium* plant association described for the Umpqua National Forest (Atzet and others 1996). This vegetation type has one of the lowest values for stand density index of any plant association in the Pacific Northwest. If the initially computed relative density index is greater than 1.5, it is set to a final value of 1.5.

REM 3.5.9. An average crown ratio (**crhat!**) for the species of the current tree record is expressed as a scalar value between zero and ten. Species-specific Weibull "b" and "c" parameters are computed from the **weib** series parameters and the average crown ratio. The "b" and "c" are bounded with minimum values.

REM 3.5.10. Tree records having a dbh less than one inch retain their original crown ratios until they exceed one inch dbh. All other records are assigned a new tree crown ratio based on a scaled rank ratio, bounded between 0.05 and 0.95.

REM 3.5.11. An average percentile value in the Weibull density distribution is given for the current species. The difference between **rankratio!** (the value for the tree record) and **pcthat!** (the species average) is computed. Depending on whether the value of the difference is negative or positive, the value of the average crown ratio is reduced by or increased by 0.1 until the difference of **rankratio!** and **pcthat!** equals or approximates zero.

REM 3.5.12. The newly adjusted value of **crhat!** is multiplied by ten to give a percent. The crown ratio from the previous year (expressed as a decimal fraction) is also multiplied by 100 to give a percent. The difference between the two percentages and the ratio of the difference to the old crown ratio (as a percent) is then calculated.

If the ratio of the difference to the percent crown ratio lies between -0.1 and 0.1, the crownratio for the record in the current year changes from the previous year automatically by that difference. Any difference less than -0.1 decreases the crown ratio by 0.1, and any difference greater than 0.1 increases the crown ratio only by 0.1. In effect, no crown ratio can naturally change by more than ten percent in any year.

REM 3.5.13. Crown length from the previous year is calculated using the old crown ratio and the current year height for the tree record. The maximum crown ratio possible is calculated under the assumption that all height growth occurred without any crown recession at the base. If the current estimate of the crown ratio exceeds the maximum possible crown ratio, the current year crown ratio is reduced to the maximum possible crown ratio. The final crown ratio value is then checked to see that it is bounded between 0.1 and 0.95. Adjustment is made if the crown ratio value falls outside these bounds.

4.3.6. CULTURE

Function - Model the effects of human economic behavior on stand composition, structure, development, and production of forest stands

Variables Imported: alive%, crownratio!, dbh!, ddbh!, hgt!, maxreccount%, num!, reccount%, species%, year%

Variables Exported: cutnumber!, cutting%, goal!, lastentry%, maxreccount%, num!, pileburning%, plant!, planting%, reccount%, scraping%, targetspecies%

The version of the subprogram CULTURE presented here is just one example of a combination of stand management activities possible for forest stands in the Diamond Lake pine mushroom management area. Management activities modeled here refer to stand 214 at the Diamond Lake Ranger District. Users can devise other formulations to simulate a wide variety of management practices.

This subprogram emphasizes silvicultural practices and timber harvesting. Practices are targeted to use the landscape as a testing ground for hypotheses about ways to increase the production of pine mushrooms. In the current subprogram, the hypothesis tested is the practicality of creating a multi-storied canopy with vigorously growing trees to increase pine mushrooms yields. Management practices are intended to open the canopy to let more energy and water reach the soil surface and to speed up organic decomposition and nutrient cycling.

REM 3.6.1. A local dimension array **prefer%** is established in year zero. The array contains information about the status of Pacific silver fir trees for possible harvest in year zero. Trees with a "yes" value for **prefer%** are designated for retention based on their robustness as indicated by crown ratio. Another local array variable **tally!** counts regeneration of small trees to make sure that regeneration of targeted species is adequate.

Forest management activities, such as cutting, burning, and tree planting, are represented as binary variables. Their initial values are "no." In the course of the subprogram, they are switched "yes" to signal management activities for the current year. Other variables count the number of trees of a particular species within a dbh size class.

REM 3.6.2. All values for the array variable **cutnumber!** are reset to zero. If trees are cut in a given year, the number of trees cut from each record is held in the variable **cutnumber!**. Array variables referring to individual species are also set to zero.

REM 3.6.3. In year zero, western white pine, mountain hemlock, and Shasta red fir are target species for regeneration. A timber harvest and tree planting are planned for year zero as well. The variable to describe the timber harvest disturbance is held by the variable **lastentry%**. The value "disturbed" indicates that trees were removed but that no burning or scraping of the forest floor accompanied the harvest. The variable is passed to CONECROPS (section 4.3.4.) to predict natural regeneration after timber harvest.

REM 3.6.4. Tree records are sorted by species and according to their suitability for harvest. Criteria are different for each species. For Pacific silver fir, trees with crown ratios less than 0.5 are especially targeted for cutting. There is no restriction about diameter cutting limits. The goal of management is to keep Pacific silver fir trees in stands as a minor component. Vigorous trees of targeted species are desired for eventual harvesting and for maintaining resistance to fungal pathogens and mistletoe infestation.

Note: The component of lodgepole pine in the stand is minor, and lodgepole pine trees remain unharvested.

Western white pine trees with dbh's greater than one inch or tree height taller than ten feet are cut. Removal eliminates trees likely to be infested with western white pine blister rust. Some economic value may come from larger trees harvested in year zero.

REM 3.6.5. Management of Shasta red fir as a target species is more complex. Trees are treated according to three dbh classes. The largest, old-growth trees have dbh's in excess of 20 inches. None of these are cut because they may serve as focal trees for pine mushroom populations. The number of these trees per acre is tallied. Mid-sized trees between 7 and 20 inches dbh are likely to produce the bulk of timber trees and provide eventual replacement trees to the old-growth size class. Trees with crown ratios less than 0.4 are considered suitable for cutting as they are likely to be the least robust. The number of trees to be cut from each record is stipulated by the cut number variable. In the case of Shasta red fir, all trees from a tree record with low crown ratios are planned for harvest.

The same procedure is carried out for mountain hemlock as for Shasta red fir. Trees are grouped by diameter size class and designated for cutting.

Note: CULTURE precedes subprograms BOUGHS (section 4.3.2.) and CHRISTMASTREES (section 4.3.3.). This order indicates that timber harvests are designated in advance of bough and Christmas tree sales. The order of subprograms in the cycle of annual activities directed from the core program is not necessarily the actual temporal sequence of management practices during a year.

REM 3.6.6. Any restriction on numbers of trees to be cut within a diameter size class reduces the number of available trees for timber harvest. Pacific silver fir is desired as a minor component in the stand. A minimum of ten preferred trees from any size class is desired for stand diversity. If there are less than ten Pacific silver trees per acre in the stand, no Pacific silver fir trees are cut. If there are more than ten trees, but the number of trees preferred for harvesting is less than ten, all preferred trees are retained plus a fraction of the trees not preferred so that the stand total of retained trees remains at ten after the harvest.

For lodgepole and western white pine, no additional harvest restrictions are in place.

REM 3.6.7. Both Shasta red fir and mountain hemlock have targets for numbers of trees retained in each of the three dbh classes after harvest. Species targets are different for overstory and mid-sized trees. Shasta red firs dominate the tallest trees. A few of the retained trees are also mountain hemlocks. Removal of mid-sized mountain hemlock trees is intended to thwart spreading dwarf mistletoe from taller trees to smaller trees.

If the number of trees in a cohort dbh class exceeds the species-specific target for the dbh class, then the cut number for each tree record includes the fraction equal to the ratio of the target number to the pre-harvest number of trees in the dbh class. If the target is less than or equal to the pre-harvest number of robust trees in a respective dbh size class, no trees are cut. The value of **cutnumber!** remains at zero for records having dbh's within the range of the dbh class.

REM 3.6.8. Year zero activities conclude with planting blister rust-resistant western white pine stock from local provenances. Fifteen new tree records each with sixteen trees represent the planted stock. The count of live tree records and the maximum number of places held for tree records increases by ten at the same time. A random number is assigned at this time to model the mortality of small trees by the end of year four. All small western white pine trees are modeled identically as 1-foot high trees with crown ratios of 0.8. Small tree records for western white pine first appear are tallied in the model when their age since germination reaches four years.

REM 3.6.9. Targets for surviving regeneration of Shasta red fir and mountain hemlock in year four are 200 new small vigorous trees for each species in addition to 240 small western white pine trees, both planted and naturally regenerating. Regenerating trees of target species, all less than breast height, are tallied, including small young trees held in the array variable **smallnum!**. The tally of young regeneration is compared against original targets. In this instance, if less than two-thirds of the target number of regenerating trees survives until the stand examination in year four, additional trees are planted to make up for wanting regeneration.

Note: Costs of stand regeneration determined at the time of timber harvest in WOODPRICES (section 4.4.16.) are assumed to cover all subsequent planting costs.

REM 3.6.10. In the fifth year after initial timber harvest, another small timber harvest occurs to remove overstory mountain hemlock trees. Their removal is intended to reduce infection of young trees mountain hemlock trees from dwarf mistletoe in the crowns of overstory mountain hemlocks. Many of the medium-sized mountain hemlock trees are likely to have been infested already. Consequently, mid-sized mountain hemlock trees are removed during the previous harvest.

REM 3.6.11. In year 25, the first of a series of harvests in a cycle of regulated, uneven-aged management occurs. Lodgepole pines, few in number, are not harvested. Cutting goals are established for the remaining species. For Pacific silver fir, all trees taller than breast height with dbh's less than four inches are cut. Harvests of Christmas trees and boughs, calculated independently in BOUGHS or CHRISTMASTREES, may help to reduce the number of Pacific silver firs regenerating in gaps.

For the three species originally targeted, a few trees are harvested in the middle dbh size class. Fifty percent of both Shasta red fir and mountain hemlock are removed to create more space for remaining trees in that size cohort to grow. Old-growth trees remain on site even if fallen over. Small Shasta red fir trees may be reduced by Christmas tree sales. Trees with dbh's between four and seven inches are tallied for both species as well.

The number of western white pine trees is tallied for each of the three dbh classes. Western white pine trees are harvested only if they exceed a seven-inch dbh minimum cutting limit and the number of trees in that cohort exceeds 40 trees per acre. Forty is the desired number of surviving trees per acre for crop trees. Trees in the dbh range between four and seven inches are harvested if that cohort is too dense, i.e. the total trees greater than four inches is greater than 50. Thinning occurs from below for chips and for final spacing as crop trees. Trees with dbh's less than four inches are left to grow.

Pacific silver fir trees with dbh's between four and seven inches are all harvested for a remnant ten trees per acre. Numbers of western white pine are calculated for harvest. Mountain hemlock or Shasta red fir trees in excess of 32 trees per acre in the dbh subclass of trees between four and seven inches are also harvested.

Data on harvest volumes is passed to VOLUMECALC (section 4.3.15.) where product value and harvest costs are calculated. VOLUMECALC also tallies merchantable wood volume from dead trees which are not included here.

4.3.7. DEATH

Function - Calculate density-dependent mortality
Transfer dead trees into the record-keeping system for dead trees

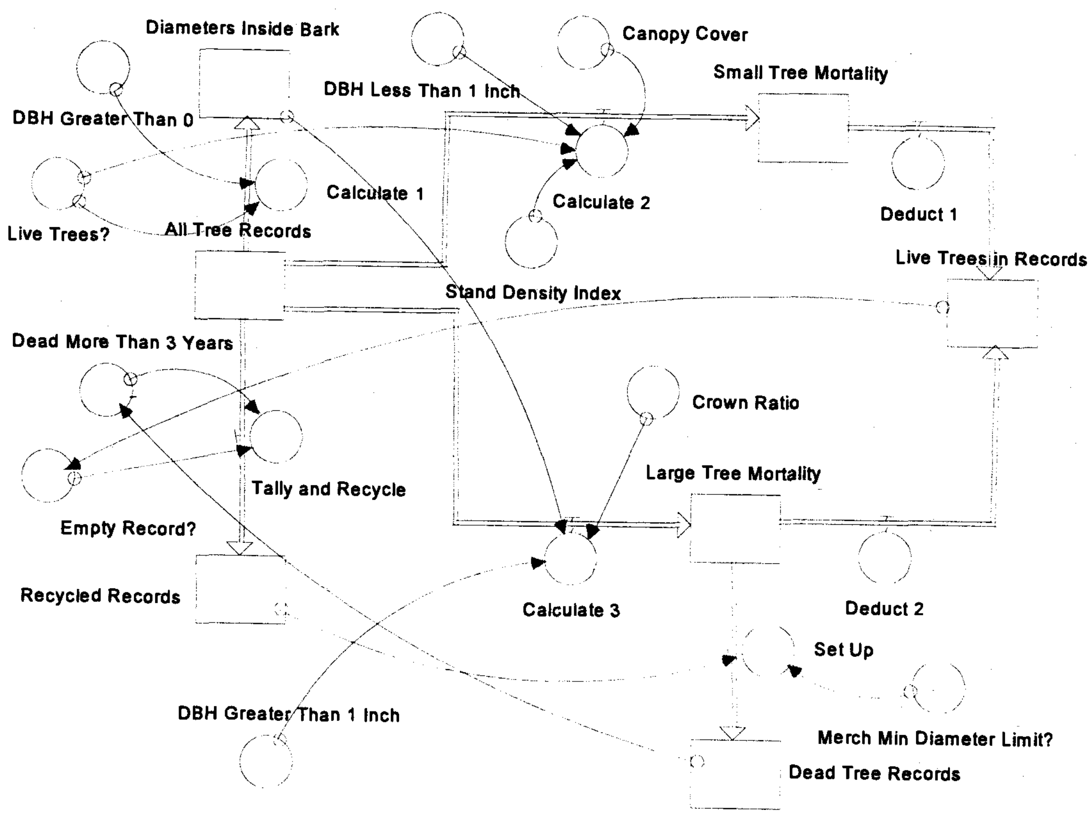
Variables Imported: age%, alive%, barkratio!, batot!, canopycover!, crownratio!, crownwidth!, dbh!, ddbh!, dght!, defect!, hgt!, lognumber%, maxreccount%, num!, prune%, reccount%, sdi!, species%, tpatot!, unprunedcrownwidth!, year%

Variables Passed: key1!, key2!

Variables Exported: age%, alive%, ba!, dbh!, empty%, free%, freecount%, hgt!, lognumber!, num!, prune%, reccount!, sdi!, species%, treedefect!

The algorithm for computing density-dependent mortality is adapted in part from the subroutine MORTS used in both the West Cascades and Pacific Northwest Coast variants of the FVS (Donnelly 1995). DEATH is called annually from the core program, except in year zero when the incoming tree list is assumed to have already accounted for annual mortality.

Figure 4.6. A schematic overview of DEATH.



REM 3.7.1. The local array variable **mortality!** is opened to track the density-dependent mortality incurred by each live tree record. Other local array variables temporarily hold data on the basal area, dbh, height, number of trees, and pruning status for tree records of recently deceased trees. The variable **addtocount%** keeps a running track of the number of tree records that need to be created in a year for holding data on newly-dead trees.

REM 3.7.2. Each tree record receives a value for the increment of diameter inside bark for the current year. The value is found by multiplying the diameter increment outside bark by the bark ratio for the tree record.

DEATH examines all tree records. Time since death for dead tree records is stored with the variable **age%**. With each call to death, **age%** for existing dead tree records increases one year. If the variable **age%** for a dead tree record is given a value greater than three, DEATH recycles the record. Recycling in this instance presumes that trees standing dead for more than three years are no longer merchantable as salvage timber. Recycling helps to reduce the number of records in an array.

Other records that are recycled include records that do no longer contain any trees, that is, when the value **num!** for a tree record equals zero, whether for live or merchantable dead trees. The binary variable **empty%** indicates with the value "yes" that a record is empty and ready for recycling. Previous attributes of an emptied record are set to zero.

REM 3.7.3. Each dead tree record being recycled has information about the number of logs in the bole, heights of logs in the tree bole, and the diameter of the small log end inside bark. This information is also deleted. Other newly-dead trees may occupy the recycled record. The variable **freecount%** keeps count of the number of the vacant records, and the array variable **free%** keeps the original record number on file for eventual use.

REM 3.7.4. Percent of the stand in gap space is assumed to be one minus the percent of canopy cover. Trees with dbh's less than one inch are considered understory trees and do not contribute to stand calculations of leaf area index. The amount of crown cover by small trees is calculated in CROWNWIDTHS (section 4.4.4.) and stored with the variable **smallcover!**. If the proportion of areal surface covered by small trees is greater than the fraction of available gap space, density-dependent mortality for small trees is calculated. A second deduction for small trees less than breast height occurs if stand density index exceeds the maximum stand density index as configured in STANDSTATS (section 4.3.12.) by trees taller than breast-height.

REM 3.7.5. A term for the sum of the quadratic mean diameter of the stand in ten years is set to zero. For each tree record containing live trees with dbh's currently greater than zero, the decade growth increment for dbh is calculated by multiplying the current annual value by ten. Under the assumption of zero mortality in the stand for the next ten years, the subprogram then calculates the total basal area occupied by all trees in ten years.

Total basal area ten years hence is then divided by total number of trees calculated at the end of the previous year to arrive at the quadratic mean diameter, **dq10!**. The basal area for the stand after calculating the current year tree growth is subtracted from the no-mortality basal area ten years hence. The result is an estimate of the maximum possible decadal increment in basal area.

Another estimate of maximum decadal increment of basal area is the sum of the current pre-mortality basal area for the current year plus the decadal basal area increment (**dba10!**) multiplied by the ratio of possible basal growth remaining in the stand. Possible remaining growth is the difference between the theoretical constant of maximum basal area minus the total basal area for the current stand basal area, unadjusted as yet for density-dependent mortality.

The variable **tree10!** estimates the number of trees in the stand ten years from now having the average quadratic mean diameter as a tree diameter. An average rate of tree mortality is calculated by subtracting the current number of trees from the number of trees ten years hence with the quadratic mean diameter as their dbh. Limits are set to the mortality. If the mortality rate should exceed 0.999 then the mortality rate is set at 0.999.

An average annual mortality rate is then computed with an equation of the form:

$$\text{AnnualMortalityRate} = 1.0 - (1.0 - \text{DecadalSurvivorship})^{0.1}.$$

REM 3.7.6. A variable to tally total dbh of trees greater than dbh is set to zero to assist in a second estimate of mortality described by Hamilton and Edwards (1976). The sum of all the current dbh's of all individual trees taller than breast height is calculated. An average (non-quadratic) dbh is calculated for the stand by dividing the sum of dbh's by the total number of trees above breast height.

Each record with live trees taller than breast height is examined. Storage variables **dbhsub!**, **ddibsub!**, and **ddbhsub!** take the value of the **dbh!**, **ddib!**, and **ddbh!** respectively for the current record. The number of dead trees from the tree record in the current year is set to zero. The relative dbh of the current tree record is the quotient of tree dbh divided by the stand non-quadratic average **dbh!**. Limits are placed on the values of **dbhsub!** and **ddibsub!**. A substitute value for **ddbh!** is computed using the current bark ratio.

REM 3.7.7. A logistic model of mortality is computed using Reinecke's (1933) stand density index relations based on the dbh value of the current tree record. The dbh cut-off point between choices for the Reinecke coefficient is five inches dbh.

The crown ratio of the record is transformed to a single-digit integer crown ratio code. The Hamilton-Edwards (1976) mortality function takes the equation form:

$$Rate = \exp(\ln((1.0 - 1.0/(1.0 + \exp(-0.210198 - 0.036595 * D - 0.165802 * CRC - 0.987133 * DUM))) + 1.0)/12.0) - 1.0$$

where Rate = the annual mortality rate;

D = is the tree dbh, with small-tree dbh's set to a minimum value 0.5 inch;

CRC = is the single digit integer code for a tree crown ratio (for example, a crownratio of 0.46 is transformed to an integer code of 5); and

DUM = is a dummy variable with species-specific values of zero or one.

Only lodgepole pine and western white pine have dummy variable values of one. Division by twelve in the equation stems from the original form of the equation representing a twelve-year mortality rate. The annual rate is multiplied by the Reinecke constant appropriate to the dbh of the current tree record. In its current form, this mortality model is based on conditions in northern Idaho.

REM 3.7.8. The first computation of mortality rate is considered again. That rate is multiplied by the basal area computed for the current year thus far. The first mortality rate is adjusted, depending on how close the stand basal area is to the maximum possible basal area. Of the two interim estimates of mortality, the higher value is chosen to represent tree mortality.

Annual mortality is computed for the individual record. Dead trees from the current record are held in the temporary array variable **mortality!**, and the amount of mortality is deducted from the number of trees represented in the tree record.

REM 3.7.9. If trees with dbh's larger than or equal to the global minimum merchantable tree diameter die, their mortality leads to opening a new dead tree record. The subprogram first sees whether there is a stock of recycled records. If a recycled dead tree record is available, the count of recycled records is deducted by one. Appropriate values from the live tree record transfer to the new dead tree record. Values for these variables remain static until the dead tree is harvested or has its record recycled in the fourth year since tree death.

In the absence of recycled dead tree records, key values for newly dead trees are stored in temporary arrays that were created at the beginning of the subprogram.

REM 3.7.10. Upon conclusion of mortality estimates and deductions for live tree records, the subprogram checks to see whether there are dead trees in need of transfer to a tree record. If the value of **addtocount%** is greater than zero, a new dead tree record is created. Data stored in temporary arrays and other characteristics are assigned to the new tree record. Individual dead tree records remain in use for at most four years after tree death.

4.3.8. LEAFLITTER

Function - Establish the composition of a leaf litter layer, if present, at year zero
Model the accumulation and decomposition of leaf litter on the forest floor in subsequent years

Variables Imported: canopycover!, decay!, leafareaindex!, leaffall!, litterdepth!, specieslai!, year%

Variables Exported: litter!, litterdepth!

The subprogram LEAFLITTER establishes the composition of the organic litter layer in year zero and uses decomposition rates for conifer leaves to predict the depth of an organic litter layer above ash/pumice soils in the Diamond Lake area. Baar and Kuyper (1993) have shown that litter depth in *Pinus sylvestris* L. plantations affects the growth of mycorrhizal fungi. Removing the organic layer significantly shifted species dominance and restored species diversity of fruiting fungi. Litter depth and composition may regulate fruiting of North American pine mushrooms in a manner similar to observation and cultural practices with the Asian pine mushroom in Korea and Japan.

One management method to decrease organic litter layers is to reduce leaf area index through tree pruning or tree cutting, for example. Modeling effects of the stand management on litter on the forest floor may determine the suitability of sites for pine mushroom production.

REM 3.8.1. With each annual call to LEAFLITTER, a local array is redimensioned to hold values for average litter density from species modeled in MUSHROOM. Figures for litter density are extrapolations from the very limited data available.[1]

Information is best described for Pacific silver fir; however, the information is available only from sites in the central Washington Cascades. Equations for rates of litter decomposition for Pacific silver fir come from studies by Edmonds (1980, 1984), Edmonds and Erickson (1994), and Edmonds and Thomas (1995). The diversity of data for Pacific silver fir allow for division of decay rates according to geographic aspect.

Average annual exponential decay rates are found for trees having a southern aspect. Annual decay rates are not constant for leaf litter. This subprogram depicts exponential decay rates themselves decaying over time. The chemical composition of litter changes over time. This change usually means that residual organic matter is increasingly resistant to decay, hence lower decay rates. Initial decay rates are highest on slopes with southern and southwestern exposures where solar radiation is more intense. Increased energy for decomposition promotes decay. Equations for northern exposures are derived from the work of Edmonds and Thomas (1995), and decay equations for other aspects come from Edmonds and Erickson (1994).

For lodgepole pine decay rates, canopy cover is the independent variable used to predict decay rates. Stands with greater than 75 percent canopy cover provide the baseline amount of leaf decay. In less dense stands, a more open canopy permits faster decay rates. Again, the model presumes that a greater amount of solar radiation and rain contributes to faster decay rates. Data for decay rates in the first year of decay come from

[1]Personal communication. 12 February 1997. Roger Ottmar, research forester, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Seattle, WA.

Taylor and others (1991); estimates of decay rates in other years come from Yavitt and Fahey (1986). All data are extrapolated from lodgepole pine forests in the Rocky Mountains.

No information about decay rates of western white pine foliage presently exists. Rates for eastern white pine (*Pinus strobus* L.) needle decomposition (Berg and others 1996) are not applied because climate conditions in the ranges of each species are different. Instead, data for sugar pine from Sequoia National Park, California in Stohlgren (1988) are extrapolated to western white pine in this model.

Likewise, no information currently exists about decay rates for Shasta red fir. Stohlgren (1988) suggests that red fir and white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.) in Sierra Nevada of California have similar decay rates. Decay rates for Shasta red fir at Diamond Lake are extrapolated using closely-related or co-occurring true fir species: for north aspects, rates from noble fir in western Oregon (Fogel and Cromack 1977) and for all other aspects, the previously cited rates for Pacific silver fir.

Decay rates for mountain hemlock come from two sources. Decay rates in the first year since litter fall are based on leaf area index from work by Cromack and others (1991). Rates for subsequent years are based on extrapolations of findings by Edmonds and Thomas (1995) for western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) in Olympic National Park.

REM 3.8.2. In year zero, another local array is redimensioned to estimate percentages of litter remaining on the forest floor between zero and five years. A two-dimensional array variable **litter!** is initialized to hold quantities of leaf litter classified by species and by time in years residing on the forest floor. The corresponding share of leaf litter from one species is figured as the fractional value composed of the species-specific contribution in relation to total leaf area index. The array variable **specieslai!** from LEAVES (section 4.3.9.) furnishes the information for leaf area indices of individual species.

Contributions from litter fallen in each year up to five years ago are summed to give a weighted average percentage of litter by species. This method assumes that forest composition has been stable in the years immediately preceding the planning period. An estimate of dry-weight mass from a particular species is given by multiplying together the species share of leaf area index, the litter depth in centimeters, and the litter density expressed in grams per cubic centimeter. The mass for each litter component is the product of the percent contribution to litter and the entire mass estimate for the species.

Data for litter remaining longer than three years on the forest floor is scant. Species-specific decomposition rates for year four and year five assumed to be identical with those for year three.

REM 3.8.3. In subsequent years, litter from each age class and each species is aged one more year and its mass is reduced by the age- and species-specific decay rate. Litter in year six is assumed to have decomposed enough that it has begun to move down the soil column. Evidence for this effect is found in the soil profiles from the area (described in SOILENERGY, section 4.4.13.), which have higher organic matter content in lower soil layers than in the A1 layer.

Inputs of leaf litter from the current year are compiled in LEAVES and transferred to LEAFLITTER by way of the array variable **leaffall!**. Litter depth at the end of the current year is set to zero. Then, for each species and each age class of litter, contribution to litter depth is summed together.

Note: Assuming constant litter densities and constant rates of decay fails to account for the changes in physical structure and chemistry of litter (Harmon and others 1990). The crude structure of this submodel reflects the little information documented for litter densities and decay rates. One fundamental assumption of the model is the evenness of soil litter depth throughout a stand. This assumption is incorrect in stands with considerable canopy gap and resulting uneven distribution of litter and rates of decomposition across the forest floor.

4.3.9. LEAVES

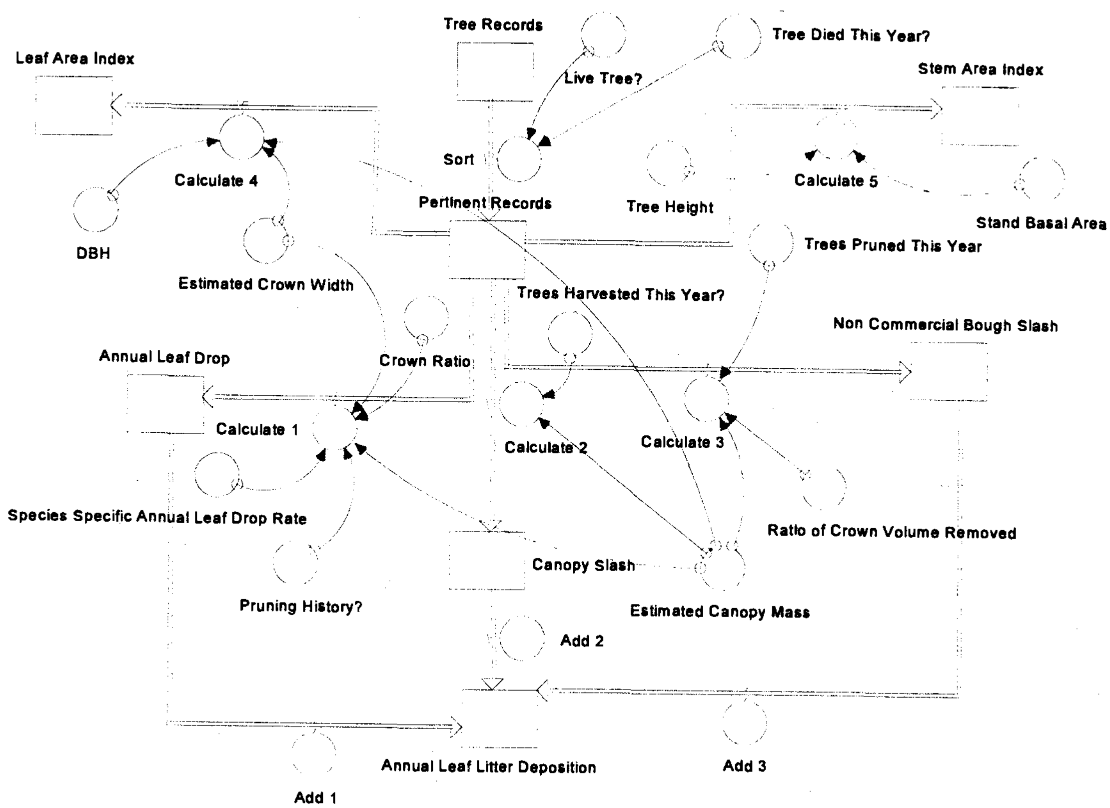
Function- Calculate leaf area index at least once annually
Calculate the contribution of each species to leaf area index in year zero
Calculate the mass of conifer foliage added to the forest floor
Predict crown volumes and crown masses of both pruned and unpruned trees

Variables Imported: age%, alive%, boughprice!, branchmass!, calling%, crownratio!, crownwidth!, cutnumber!, cutting%, dbh!, empty%, foliararea!, foliarmass!, hgt!, num!, prune%, prunetag%, pruning%, ratioremoved!, reccount%, species%, tpatot!, treespecies%, unprunedcrownwidth!, year%

Variables Exported: canopycover!, converttomass!, leafareaindex!, leaffall!, relden!, specieslai!, stemareaindex!, woodresidue!

LEAVES is called annually after tree growth and density-dependent mortality have occurred. The subprogram performs multiple functions regarding the effects of forest canopy on stand conditions during stand simulations. The herbaceous and shrub layers are naturally sparse in the Diamond Lake pine mushroom management area and are ignored here in leaf area index calculations. In years when management activities reduce foliage in the stand through tree cutting or tree pruning, the subprogram is called a second

Figure 4.7. A schematic overview of LEAVES.



time to recalculate canopy characteristics, weight, and changes to crowns of individual trees.

REM 3.9.1. Invoking the subprogram sets values of variables being calculated in the subprogram back to zero. A variable **woodresidue!** tracks the amount of woody down material left on site after management activity. Its value is held static so that residue values are maintained between calls to the subprogram during the same simulation year. In year zero, values of leaf area indices for individual species are also set to zero. These values are used to establish past contributions by individual species to the organic litter layer in LEAFLITTER (section 4.3.8.). In year zero and following years, the subprogram also tracks additions of leaf litter annually from species with the array variable **leaffall!**.

REM 3.9.2. Data for the fraction of leaf mass lost from annual shedding come from personal observations.[2] Data and rates for leaf drop are poorly know and present a gap in the model knowledge. Conversions to dry weight from wood volumes expressed in cubic feet come from Hartman and others (1976) and Snell and Brown (1980). Values used here for mountain hemlock are from western hemlock. Shasta red fir uses data for Pacific silver fir.

REM 3.9.3. Each call to LEAVES inspects all live tree records and some dead tree records. In the first call to LEAVES annually, records for large trees having died in the current year are also included for their contribution to leaf drop during the current year. Trees without a history of pruning are directly assigned a crownwidth from CROWNWIDTHS (section 4.4.4). Crown volume is calculated at the same time. All tree species except lodgepole pine are modeled with conical crowns. Lodgepole pines are modeled with cylindrical crowns (Oliver and Larson 1990). Estimated crown volumes of pruned and unpruned (full-crowned) trees are calculated and compared. The variable **ratioremoved!** is the decimal fraction of a full crown by which the pruned tree crown is reduced; for unpruned trees the value of **ratioremoved!** is always zero. See CANOPYMASS (section 4.4.3.).

REM 3.9.4. If trees have been pruned in the past, discrepancies may arise in foliar volumes between pruned trees and the presumably unpruned trees on which allometric equations are based. For trees, either live or recently dead, with a history of pruning, crownwidth predicted from CROWNWIDTHS is modified. The variables **key2!** and

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[2]Personal communication. 16 October 1996. Charles Bolsinger, resource analyst, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

key1! are dbh values for which the annual lateral extension of the crown reaches limits to rates of extension. Trees previously pruned are assumed to have faster rates of lateral crown extension based on key dbh values. In the model, crowns of pruned trees expand at a faster rate than crowns of unpruned trees until the crown width of a pruned tree attains the crown width of unpruned trees having the same dbh. After that time, pruned trees assume the same crown expansion rate as trees with unpruned crowns. Information about tree crown response to pruning is poorly known (Maguire and Petruncio 1995) and not described for any of the species in this model.

Although crown widths of pruned trees may reach modeled widths of unpruned trees over time, crown volume may continue to be smaller because the crown length remains reduced. Pruned canopy volume is compared to the unpruned canopy volume to provide an estimate of the ratio of foliage volume and mass reduced in years after tree pruning.

REM 3.9.5. The amount of foliage from needle drop is estimated from the values of **litterfall!** for each live tree. Each live tree contributes the portion of its canopy mass that is equal to the average annual needle rate. Trees that have died in the current year as the result of density-dependent mortality contribute their entire mass of their crowns to stand litter fall. The litter fall from individual trees is sorted by species with the variable **leaffall!**. Additions to litter fall are converted from dry weight in pounds to dry weight expressed in kilograms. The information from **leaffall!** is used in LEAFLITTER to calculate changes in the depth of the organic litter layer.

REM 3.9.6. In years when timber is cut or trees are pruned, LEAVES is called a second time to update leaf area index and calculate the amount of additional leaf litter left on the forest floor from pruning and logging. For newly pruned trees, the volume of canopy lost is reckoned on the basis of pruning height as determined by dbh class.

REM 3.9.7. In instances where pruning of species with no commercial value in the current year occurs, the bough price established in BOUGHS (section 4.3.2.) signals that the pruned bough mass is not removed from the site but remains as litter on the forest floor. The foliar mass left on site is calculated in kilograms as the product of the canopy foliar mass, the ratio of the volume of canopy removed during pruning, and the number of trees represented in the tree record. Otherwise, for trees with marketable boughs, only the mass equal to the estimated defect rate is left on the forest floor.

For pruned trees, all branch mass accumulates on the forest floor. Its units are calculated in English tons. Tags to mark pruned trees are switched to "no" values after deductions of canopy mass are concluded.

REM 3.9.8. In years when tree cutting takes place, the litterfall for felled trees is calculated. If the tree had been pruned either in the current year before cutting or in previous years, the foliar mass already taken from the stand for boughs is deducted from the litterfall contribution of the cut tree. The entire foliage mass of the tree at the time of cutting is assumed to lie on the forest floor. The model assumes that a tree cut in a given year has already contributed the amount equal to the portion of the annual rate of dropped leaves. All additions to leaf fall quantities are expressed in kilograms, whereas branch wood residues are tabulated in English tons.

REM 3.9.9. With each call to LEAVES, leaf area index, stem area index, canopy cover, and relative density are recalculated. All remaining live trees with diameters at breast height greater than one inch are included in these calculations. Deductions of foliar area deducted in pruning are taken before the leaf area from a tree record is added to the tally of leaf area index.

For canopy cover, the crown competition factor for trees in a tree record is calculated based on current crown widths. Crown competition factors are percentages of ground area covered per acre by canopies of all trees in one tree record. The sum of crown competition factors in a one-acre sample of forest is relative stand density. These values are transformed to percents and summed to give the relative density. Canopy cover is the decimal fraction of the total percent. If canopy cover exceeds a value of one (or if relative density is greater than 100), the canopy cover value is set to one.

In year zero, the relative contribution of each tree in square feet to leaf area index is calculated for each species with a running total. These values along with **leaffall!** values are transferred to LITTERFALL.

REM 3.9.10. The method for calculating stem area index here is extrapolated from the equation established by Sampson and Smith (1993) for lodgepole pine in Colorado:

$StemAreaIndex = \pi * (QMD/2) * MeanTreeHeight * TPH * 0.0001$, where

QMD = the quadratic mean diameter in meters;

MeanTreeHeight = the average metric height of trees greater than breast height;

TPH = the number of trees per hectare; and 0.0001 is the conversion factor from square meters to hectares.

The unitless result is the same as for a square foot calculation per acre (43,560 square feet).

4.3.10. MUSHROOMYIELD

Function - Predict the yield amount of the pine mushroom harvest per acre of forest

Variables Imported: calendaryear%, cutting%, exchange!, flushes%, mushroomprice!, mushroompricescenario%, mushroomyieldscenario%, springsoilwater!, year%

Variables Exported: mushroommass!, mushroomvalue!

REM 3.10.1. In the current version of the model, no pine mushroom harvest occurs in years when timber is harvested. All timber harvests are assumed to occur in the autumn, that is, at the same season as pine mushroom harvests. An annual harvest for pine mushrooms is foregone to permit unimpeded timber harvest operations.

REM 3.10.2. In years when timber is not being harvested, pine mushroom harvests may take place. Knowledge about environmental conditions conducive to producing North American pine mushrooms is limited. Twelve scenarios are presented in MUSHROOMYIELD for predicting harvest quantities of pine mushrooms under assumptions about the productivity of pine mushrooms. The user specifies a mushroom yield scenario in the core program to model pine mushroom harvest weights.

Many of the scenarios depend on probabilistic frequencies of yields based on crop yields in the recent past and on weather data. Annual production of mushroom crops is variable in both Asia (Park and others 1995) and in the Pacific Northwest (Pilz and Molina 1996). Data on crop yields and frequency distributions used in this subprogram are based on records of pine mushroom yields from a mixed conifer-hardwood forest site near Cave Junction, OR., 160 km to the southwest and at an elevation of 390 m, more than a thousand meters lower than the management site near Diamond Lake, OR, and from Chemult, OR, 32 km from Diamond Lake.

Decisions founded on extrapolated data are prone to error. The range of scenarios based on extrapolated data is useful, however, for a sensitivity analysis. Robustness of results under different circumstances can indicate to land managers and other interested people the potential benefits from management of pine mushroom resources despite uncertainty about financial benefits, ecosystem processes, and management practices to promote production of pine mushrooms.

Table 4.2. gives an overview of the twelve scenarios presented in the following paragraphs for pine mushroom harvest yields at the Diamond Lake pine mushroom management area. Andrew Moore has maintained a five-year record of pine mushroom production from a commercial site near Cave Junction, OR. In the first scenario, probabilities for harvest yields during the five years are considered equally probable for any future year in the planning period modeled here. The range of harvest yields at Cave Junction spans from 0.007 to 4.1 pounds per acre. These yields are substantially higher than the two-year record available from Chemult, OR, lower than yields known from coastal sites in Oregon, and lower by an order of magnitude of yields from managed forests in Korea for the Asian pine mushroom (Park and others 1995). Cave Junction yields are halved to approximate yields at Chemult and are applied to conditions at Diamond Lake.

A review of the weather records from Cave Junction, OR, kept at the USDA Natural Resource Conservation Service Office in Portland, OR, for the period 1962 to 1995 shows that the weather events in September 1994 were unprecedented for the early cold wave followed by a long spate of hot weather (figure 4.8.). Each of the years with a complete weather record for September through November was matched against the maximum, minimum, and average daily temperatures for four of the five years (that is, between 1992 and 1995) for which pine mushroom harvest data are available.

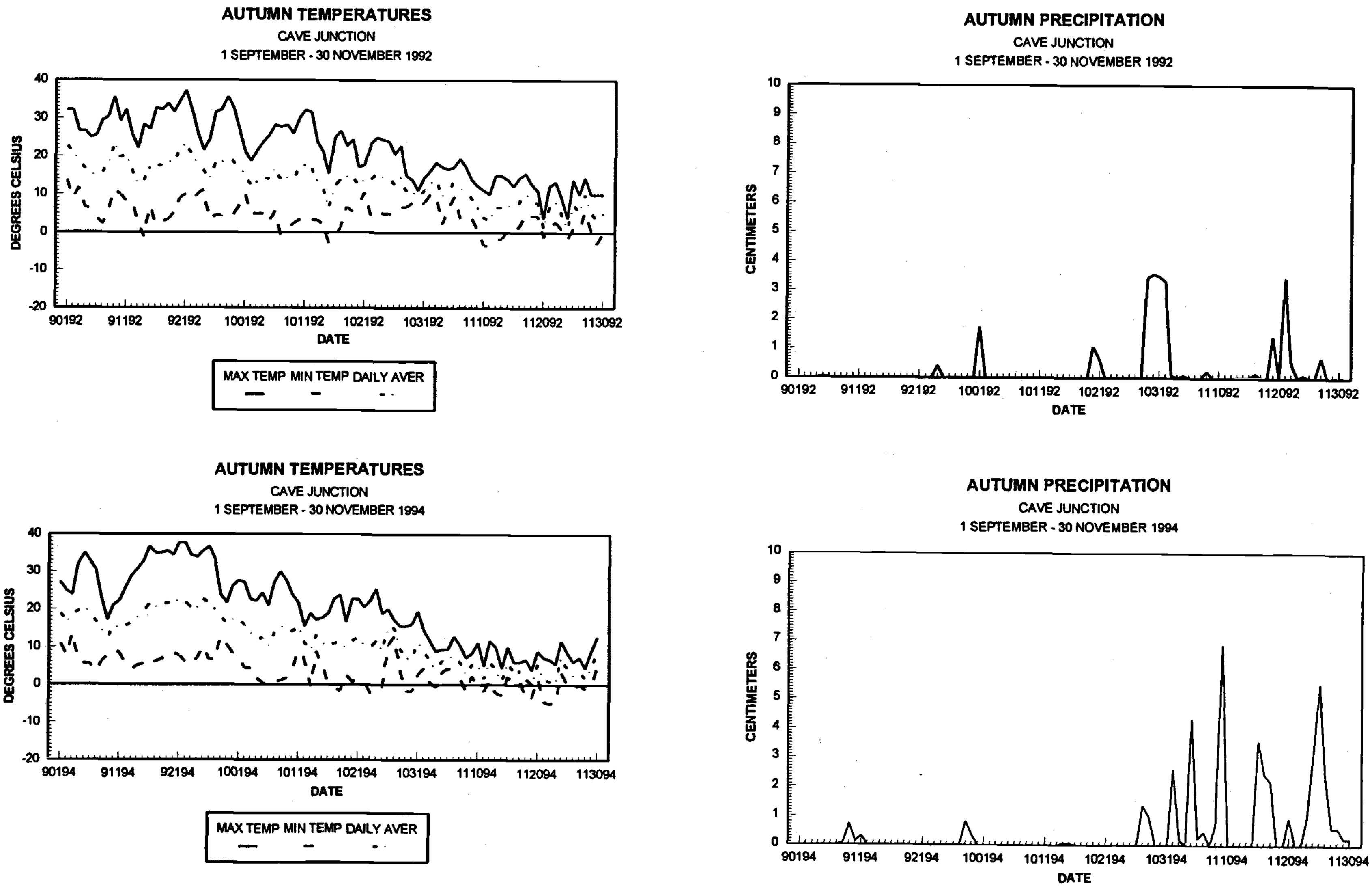
For nearly three-quarters of all years with weather data, deviation from the harvest data year weather was least with 1992 data, coincidentally the year with the greatest production. The year 1994 with anomalous weather and coincidentally the lowest production did not compare similarly to weather patterns of any other year. Basing patterns of pine mushroom productivity on weather data has been done in Japan and Korea (Kang and others 1989, Cho and Lee 1995, Park and others 1995). The current sample of pine mushroom production linked to weather conditions may be a biased sample of the historical record or may perhaps presage climate change. Correlating

Table 4.2. Scenarios for modeling pine mushroom yields at the Diamond Lake pine mushroom management area, Umpqua National Forest, Oregon.

Scenario	*Source of Harvest Data*	*Basis for Yield Response to Management*
1	Cave Junction	Harvests and weather patterns 1992-1996
2	Cave Junction	Harvests 1992-1995, weather patterns 1962-1995
3	Cave Junction	Doubling harvest yields from 1992-1995, weather patterns 1992-1995
4	Cave Junction	Doubling harvest yields from 1992-1996, weather patterns from 1962-1995
5	Cave Junction	Doubling harvest yields 1996-2000, five-fold yield increase 2001-2020, weather patterns 1962-1995
6	Cave Junction	Doubling harvest yields 1996-2000, five-fold yield increase 2001-2020, weather patterns 1992-1995
7	Chemult	Harvest yields 1994-1995
8	Chemult	Doubling harvest yields 1996-2020
9	Chemult	Doubling harvest yields 1996-2000, five-fold yield increase 2001-2020
10	None	Harvest failure 1996-2020 following implementation of management
11	None	Harvest failure 1996-2020 following clearcut timber harvest
12	None	Mechanistic model based on hypothesized relations between composite weather data, 1980-1995, and forest stand structure

weather patterns since 1962 on the basis of similarity among years between 1992 and 1995, however, provides a different weighting for the pine production from the Cave Junction site. The probability of a weather pattern and corresponding low pine

Figure 4.8: Weather patterns for a high production year (1992) and a low production year (1994).



mushroom production similar to that in 1994 is reduced from 0.20 to 0.052 from scenario one to scenario two.

A third scenario extrapolates the production outputs from Cave Junction to suppose that the productivity at Diamond Lake doubles after five years of stand management designed to increase pine mushroom productivity. The fourth scenario is a reprise of the probability distribution of scenario two with doubling of production from scenario three.

Scenario five assumes doubling crop yields for the first five years after management implementation and in the sixth and following years, production increases five-fold. Probabilities are distributed as for scenario one. Scenario six takes the same pattern of increasing production with the probability distribution used in scenario two.

Scenario seven uses data from a pine mushroom study site in Chemult, OR, provided by Gerald Smith. Data are available for two years, 1995 and 1996. Yield figures from each year have an equal probability of occurring. Chemult lies just east of the Cascade Crest and has a colder and more arid climate than Diamond Lake. Harvest quantities in Diamond Lake may be more similar to harvest yields in Chemult. Scenario eight uses the Chemult data and assumes that pine mushroom productivity doubles immediately after implementation management designed to augment productivity. Scenario nine uses the Chemult data and assumes that pine mushroom productivity doubles immediately and increases five-fold beginning in year six of the planning period.

Scenario ten poses a "failure" scenario. It assumes that pine mushroom productivity goes to zero after initial investment in management for pine mushroom productivity and that remedial stand management to augment financial yields is not implemented subsequently. Scenario eleven assumes a clearcut harvest in year zero to maximize immediate financial benefits from liquidating timber stocks on site. Stand management of the clearcut includes stocking the site with rust-resistant western white pine and natural regeneration with lodgepole pine. As in scenario ten, pine mushroom harvests fail to occur during the 25-year planning horizon.

Scenario twelve uses hypothesized relations between weather data, with its associated inputs of water and energy to the A1 soil layer, and pine mushroom productivity. The amount of water penetrating the soil in the spring is hypothesized to increase the capacity for mycorrhizal connections between fine roots of trees and fungal mycelia. Water and soil temperature as mediated via several pathways in the forest canopy are modeled as triggers to primordia initiation and sporocarp development as intervals of falling soil temperatures and increased soil water produces mushroom flushes. The mechanisms for determining the amount of soil water in spring and the number of flushes are driven by WEATHERDATA and calls to GASHCANOPY (section 4.4.7.) and SOILENERGY (section 4.4.13.).

Quantities of production are based on a hypothetical maximum production of 4.1 lbs per acre, the largest quantity recorded to date at the Cave Junction study site. Ordinal values for the amount of spring soil water and the number of flushes projected for the autumn are multiplied together. The resulting value divided by sixteen is the percent of the hypothetical maximum production obtained from the study site. The final weight in pounds per acre is a projected annual crop from the Diamond Lake area.

REM 3.10.3. A call is made to the subprogram MUSHROOMPRICES (see section 4.4.8.) to obtain an average market price in U.S. dollars per kilogram for pine mushrooms in North America for the current year. The average annual price is multiplied by the harvest yield and divided by 2.2046 to estimate the total dollar value of the annual crop on site in pounds per acre.

4.3.11. NETPRESENTVALUE

Function - Calculate values and volumes of timber and non-timber products from agroforestry systems during the first 25-year planning cycle
Discount product values with one of four discount rates
Track forest-product based employment

Variables Imported: boughmass!, boughvalue!, conevalue!, jobs!, mushroommass!, mushroomvalue!, timbervalue!, timbervolume!, woodresidue!, xmasvalue!, year%

Variables Exported: boughmass!, boughmass25!, jobs!, mushroommass25!, mushroomvalue!, npv!, timbervolume!, timbervolume25!, totboughvalue!, totconevalue!, totmushvalue!, tottimbervalue!, totxmasvalue!

In NETPRESENTVALUE, values of annual products are expressed with four discount rates. Discount rates express time preference for receiving benefits from the forest stands. A ten-percent discount favors receipt of financial benefits sooner rather than later. A smaller annual discount rate of one percent indicates an increased preference for financial benefits spread more evenly over time.

REM 3.11.1. Current year net values are sale values of forest products less costs to get products to purchasers of the raw materials. Values and volumes for both timber and non-timber forest products and associated employment data are stored in this subprogram. Variables for employment, boughs, mushrooms, and timber volumes are held static in NETPRESENTVALUE to retain their values between calls to the subprogram. Total values of products are set to zero in year zero only.

REM 3.11.2. Each year the weight or volume of products is added to 25-year totals. Employment is accumulated in the same manner. Values of annual net product harvest receipts are discounted with one of the four discount rates: 0%, 1% , 4%, and 10%. Receipts of a product from the current year are added together with receipts of the same product from other years and discounted with the same rate.

REM 3.11.3. After each simulation of a 25-year planning cycle, all variables destined for output files are first set to zero. All products for all years with the same discount rate are totaled together to provide the net present value (**npv!**) of particular agroforestry system production during the twenty-five year period. Other combinations may be separated to obtain totals of individual products.

Data about financial returns from each simulation are stored in an output file. Sets of output data for a series of Monte Carlo simulations are subsequently analyzed statistically outside MUSHROOM.

REM 3.11.4. The product variables imported with production values for the current year are returned with zero values to the core program.

4.3.12. STANDSTATS

Function - Calculate stand basal area, tree per acre, quadratic mean diameter, and stand density index

Variables Imported: dbh!, hgt!, num!, reccount!, species%, year%

Variables Exported: batot!, lpbasalarea!, qmd!, sdi!, tpatot!

Stand-level data is generated two to three times annually to provide current information to subprograms before and after density-dependent mortality and whenever pruning or tree harvests occur.

REM 3.12.1. Variables for computation are initially set to zero. Tree records with live trees taller than breast height are included in tallies by STANDSTATS. Basal areas of individual trees are calculated in square feet and then summed together for total stand basal area at breast height. The number of trees comprising that total is tracked at the same time.

Basal area of lodgepole pine trees is tallied for use in BOUGHS (section 4.3.2.) to determine the appropriate crown ratio limit for pruning lodgepole pines.

REM 3.12.2. If the number of trees taller than breast height equals zero, the weighted quadratic mean diameter and weighted average basal area are set to zero. Otherwise, the quadratic mean diameter and mean basal area are calculated with conventional formulas. Stand density index as defined by Reinecke (1933) is then derived.

4.3.13. STUMPAGEPRICING

Function - Direct the process of calculating market stumpage prices for timber products harvested under agroforestry management

Variables Imported: calendaryear%, cutnumber!, cutting%, reccount%, valuewoodproducts!

Variables Passed: alpha!, beta!, betamultiplier!, conversion cost!, cvts!, dbh!, functionnumber%, hgt!, normal!, num!, prune%, prunedportion!, scribner6!, species%, unbiaseddib!, woodpricescenario% **plus** variables for lumber and chip prices

Variables Exported: timbervalue!

STUMPAGEPRICING estimates the stumpage value of both live and salvage timber. Individual values for records of live and dead trees are calculated first and summed give an annual total.

REM 3.13.1. If trees have been harvested in the current year, STUMPAGEPRICING calls WOODPRICES (section 4.4.16.) to receive a single set of wood product prices and production costs for the year.

REM 3.13.2. If a tree record has a positive value for the array variable **cutnumber!**, previously set in CULTURE (section 4.3.6.) and the tree dbh equals or exceeds the minimum tree diameter for chipping, the record is forwarded to WOODUSE (section 4.4.17.) to ascertain the current stumpage value of trees represented by the record.

Tree records with a positive value for **cutnumber!** or trees with diameters smaller than the chipping diameter limit are assigned a zero value for **valuewoodproducts!**

REM 3.13.3. The value of wood products from a single tree of a record is multiplied by the number of trees cut from that tree record in the current year and added to the running total of **timbervalue!**. The variable **cutnumber!** for each tree record is set back to zero once the total timber value of stand trees is calculated. The total annual timber value is then sent on to NETPRESENTVALUE (section 4.3.11.).

4.3.14. TREEGROWTH

Function - Direct calculations of annual tree diameter and height growth of trees

Variables Imported: age%, alive%, batot!, canopycover!, dbh!, hgt!, maxhtgrowth!, minhtgrowth!, num!, reccount%, tpatot!, year%

Variables Passed: batot!, crownratio!, dbh!, ddbh!, functionnumber%, potentialheight!, relden!, siteindex!, slope!, species%, year%

Variables Exported: barkratio!, dhgt!, hgt!, pctile!, record%

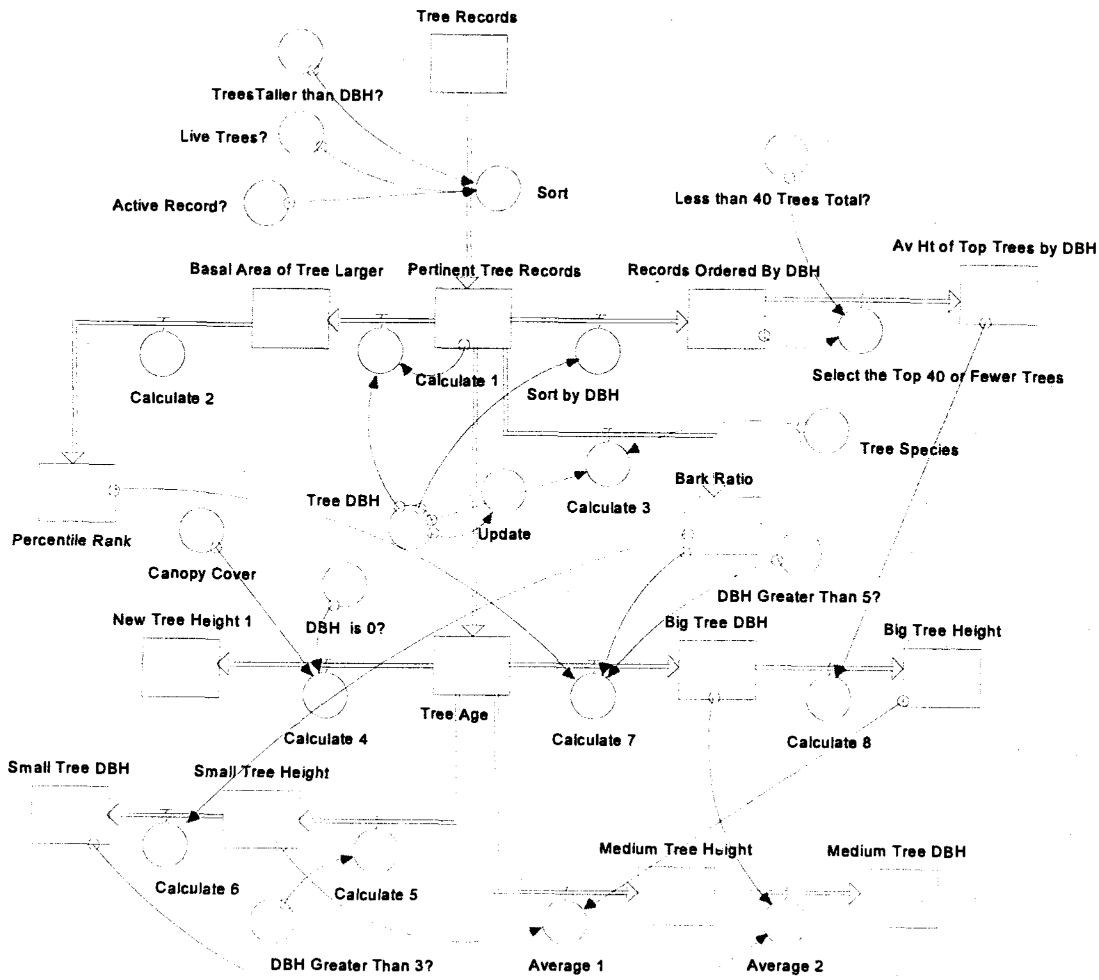
The algorithms for diameter and height growth of trees taller than breast height come from the routines AVHT40 and BRATIO in the West Cascade and Pacific Northwest Coast variants of the FVS (Donnelly 1995).

REM 3.14.1. The first task in TREEGROWTH is calculating the average height of the 40 trees with the largest dbh's from the one-acre stand sample. The variable value **avht40!** is used to calculate diameter increment at breast height of larger trees. Three local arrays are established to hold the dbh's, heights, and numbers of trees for live tree records. The arrays create a series of tree records sorted by ranking the dbh's of tree records. Array size is set to one more than the number of live tree records to accommodate the initializing record in each of the local arrays with zero values.

REM 3.14.2. The first sorting of tree records excludes from further consideration all records for dead trees, any live tree records for which there are no live trees remaining, and all records for small trees having heights less than breast height.

REM 3.14.3. A tree record not excluded thus far has its dbh compared to the dbh's of previously read tree records. Previously read records are arranged with increasing record pointer value (**move%**) in descending order of dbh magnitude. The comparison continues until the difference between the dbh of the current record becomes less than a

Figure 4.9. A schematic overview of TREEGROWTH.



dbh value in the **move%** sequence of dbh values. After all records are examined, the dbh value with the lowest **move%** value (that is, one) represents the largest dbh in the stand.

REM 3.14.4. In some instances the difference between the dbh of the current tree record and the dbh being compared may equal zero. Then, the tree height for the current tree record **hgt!(record%)** is compared with the paired height value **hgttemp!(move%)**. In cases where the difference of **hgt!(record%)** minus **hgttemp!(move%)** is greater or equal, the value of the difference is set at the value of one. This value ends the iteration process. Should the difference of the two heights be negative, the iteration process continues. If the current record has a tree height higher than a temporary dbh value in the ordered series, the current record preempts the dbh, height, and the tree number at the **move%** pointer position. Otherwise, the current record continues on to make a comparison with the record with the next highest pointer number in the **move%** sequence.

REM 3.14.5. The counter array value based on descending size of dbh is increased by one for each suite of **dbhtemp!**, **hgttemp!**, and **numtemp!** variables being moved to a higher pointer value beginning in reverse order down to the current value of **move%**. The counter variable **place%** proceeds down to the current value of **move%**, where the current live tree record value for dbh is then inserted into the array of dbh values.

REM 3.14.6. Variable values for the total number of tall trees, for the sum of heights of the tall trees, and for the average height of the 40 trees with the largest dbh for the year are given initial values of zero.

A counter variable (**count%**) tallies the number of trees with the smallest **move%** values until enough trees are collected. The variable **count%** increases by one with each tree record called up in a single iteration of the DO LOOP. The tree height for the record is multiplied by the number of trees for the record and is added to the sum of heights of the tall trees. Also, the number of trees for the record is added to the total number of tall trees.

These additions continue until one of three conditions occurs: (1) the total number of tall trees exceeds 40; (2) the total number of tall trees equals the total number of live trees per acre with heights taller than breast height; or (3) none in the stand have heights taller than breast heights, after all tree records have been reviewed. In the second case, the total number of standing trees is less than 40 trees per acre - a condition that might occur in stands with retention trees after extensive tree cutting.

REM 3.14.7. If the number of tall trees exceeds 40, the excess number of trees is calculated. The product of the number of excess trees times the tree height of the last record read, that is, the current value of **hgttemp!(count%)**, is deducted from the sum of tall tree heights. When the number of tall trees is less than 40, there is no deduction.

If there are no trees present or no trees taller than breast height in the stand area, the average height of trees with the largest dbh's automatically becomes zero. Otherwise the height for **avht40!** is the quotient of the total of tree heights divided by the number (40 or fewer) of tall trees.

REM 3.14.8. A second task determines the percentile ranks of tree records by their basal area at breast height. Percentile ranking based on basal area is one variable used in calculating diameter growth of larger trees. Three local arrays calculate basal area, the amount of stand basal area from trees with basal area larger than that of a given tree record, and the percentile ranking on the basis of amount of larger basal area.

REM 3.14.9. The percentile ranking and amount of basal area for all tree records are both set to zero initially. Only records containing live trees are considered. As each record is called, all other records with live trees are reviewed to see which tree records contribute to the stand basal area of trees larger than the individual trees represented by the current tree record. A running total, kept in **balarger!** for the current tree record, is added to when the basal area of a single tree from another tree record is larger. If two tree records have the same dbh (as for example when a record is match with itself during the review), half of the total basal area is added to **balarger!**.

REM 3.14.10. After all records have compiled values for **balarger!**, the percentile rank of each record (**pctile!**) is calculated as one minus the ratio of **balarger!** to the total stand basal area. Trees less than breast height have a percentile ranking arbitrarily set to 0.0001.

REM 3.14.11. Bark ratios are calculated for all live trees with diameters greater than breast height. Data for predicting bark ratios are unavailable for most of the species treated in the model. Parameter values from other species are substituted here in equations to determine bark ratios in the manner of the West Cascade variant of the FVS. Tree records are assigned species-specific empirical parameter coefficients developed by Walters and others (1985). Pacific silver fir and Shasta red fir are modeled to have bark ratios like those of white fir, western white pine like those of Jeffrey pine (*Pinus jeffreyi* Grev. & Balf.), and mountain hemlock like those of Douglas-fir. Lodgepole pine ratios are predicted from coefficients used in the Intermountain Region (Wykoff and others 1982).

Lodgepole pine is assumed to have a constant bark ratio equal to 0.9 for all tree dbh's. Multiplying the dbh by the bark ratio gives the diameter inside bark. All species except lodgepole pine follow Walters and others' (1985) equation form:

$DIB = a * DBH^{b}$.

The barkratio for the species is then the ratio between diameter inside bark and diameter outside bark at breast height. If the new value for the bark ratio of a tree record should exceed 1.0 or be negative, the bark ratio is set to zero. This value alerts other program functions to the invalidity of the bark ratio value.

REM 3.14.12. Each record containing live trees is included at this point to determine annual tree growth. Trees currently taller than breast height before current year growth have their ages updated by one year.

Tree records are then sorted according to dbh classes. Tree records in different categories have height growth and dbh growth calculated in different ways. The smallest trees with no diameter at breast height can have maximum annual height growth of six inches. That maximum is reduced as a function of overstory canopy cover. Tree height increments for the smallest trees are added onto tree height from the previous year.

Trees with dbh's greater than zero but less than or equal to three inches have growth calculated in SMALLHEIGHTGROW (section 4.4.12.) for height growth increment, followed by diameter growth increment in SMALLDIAMGROW (section 4.4.11.). For trees with dbh's greater than or equal to five inches, the subprograms BIGDIAMGROW (section 4.4.1.) and BIGHEIGHTGROW (section 4.4.2.) are called in that order. For trees with dbh's that fall between three and five inches, BIGDIAMGROW determines diameter growth, but height estimates from BIGHEIGHTGROW and SMALLHEIGHTGROW are both used to determine height growth. A weighting factor is calculated from the amount of tree dbh in excess of three inches divided by two, that is, divided by the difference between upper and lower limits of dbh overlap between the two height growth models. The weighted-averaged height increment is added to the height from the previous year for the current year height.

REM 3.14.13. If a tree record has its height exceeding breast height for the first time in the current year, it receives a 0.1 inch dbh automatically.

4.3.15. VOLUMECALC

Function - Calculate merchantable volumes of timber with deductions for defect and decay

Variables Imported: age%, alive%, cutnumber!, cutting%, dbh!, num!, reccount%, species%, year%

Variables Exported: cubicsalevolume!, cvts!, merchvolume!, scribner6!, standcubicvolume!, timber volume!

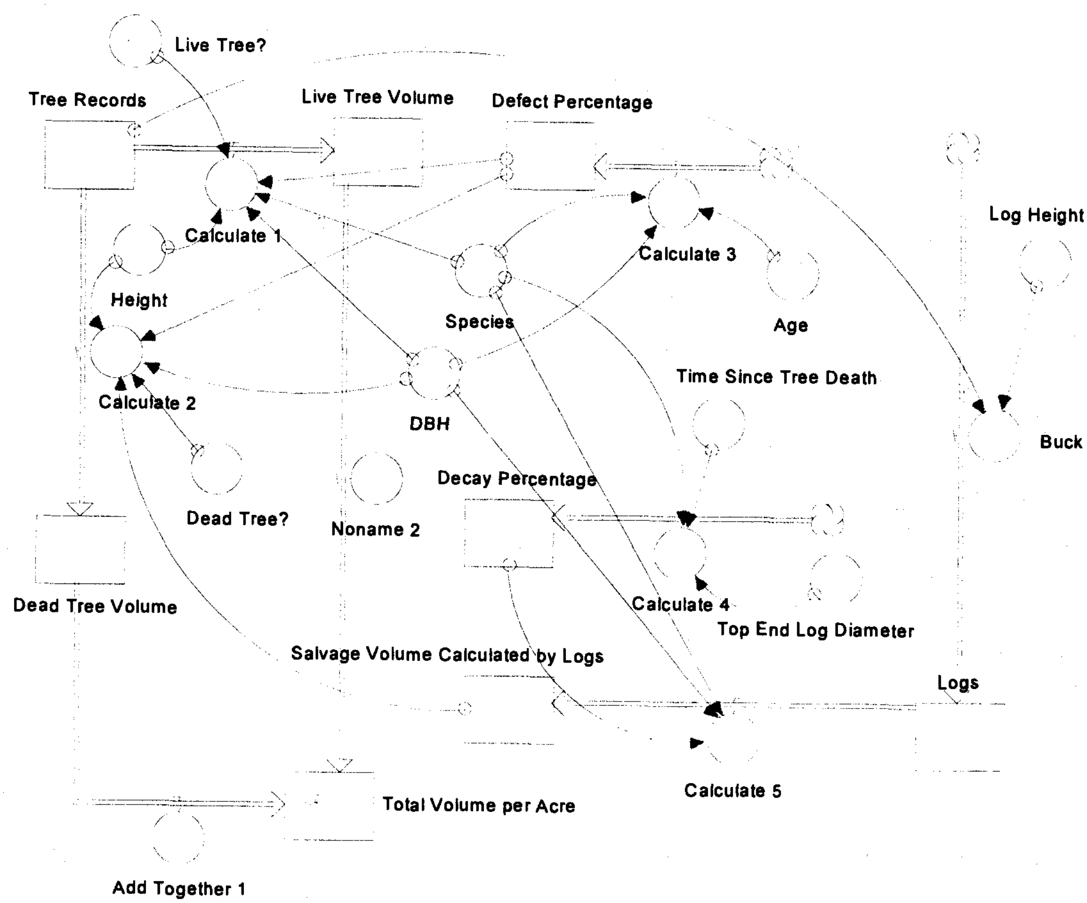
Timber from salvaged trees is treated differently than timber from live trees. Mill recovery studies conducted by the U.S.D.A. Forest Service, Pacific Northwest Research Station have shown that decay in tree boles occurs at differing rates along the bole length. Portions of trees with smaller bole diameters have faster decay rates than portions of bole at the tree base. To account for these differences, dead trees are analyzed by log length, set to a standard of seventeen feet, including a six-inch saw kerf on each end. In contrast, timber from live trees is calculated on a whole-tree basis to a standard merchantable top of four inches diameter inside bark.

REM 3.15.1. Calculation of timber volumes begins by redimensioning local arrays that carry information about dimensions of salvaged dead logs. A maximum number of logs from a tree is set to eleven. Log number is the second dimension in the salvage log array. Several calculations are undertaken: merchantable cubic and Scribner six-inch board foot volume tallies for each tree record, and annual total stand cubic and board foot volumes per acre. The values of all volume variables calculated for each record are set to zero initially. Aggregate values per acre for cubic sale volume, total standing cubic volume wood volume, and Scribner board foot volume are also set to zero.

REM 3.15.2. All tree records are forwarded to WOODVOLUMES (section 4.4.18.) to calculate values for wood volumes in Scribner board feet and cubic feet. A call to WOODDEFECT (section 4.4.15.) provides estimates for live trees of stem defect based on tree age. Dead trees have previously been assigned estimates of stem defect in the subprogram DEATH (section 4.3.7.) in the year of their demise.

REM 3.15.3. Trees with dbh's equal to or exceeding the merchantable dbh minimum for milling as lumber, as set in the core program, have equal proportions of stem defect

Figure 4.10. A schematic overview of VOLUMECALC.



deducted from the initial calculations of cubic merchantable, cubic total, and Scribner board foot volumes to give net volumes for live trees. Also, tree volumes are divided by 1,000 to give customary thousand cubic foot and thousand Scribner board foot log volume values.

REM 3.15.4. Salvaged timber as depicted in the model includes those trees dead less than four years with dbh's greater than or equal to the minimum merchantable diameter for lumber. Trees dead more than three years have already been removed from the database of dead trees in DEATH and smaller trees never enter the dead tree data base supervised in DEATH.

Species of dead trees are treated differently as the result of differing methods and results of mill recovery studies of salvaged timber. In the first selection to calculate salvage volume, logs from the hem-fir species, Pacific silver fir, Shasta red fir, and mountain hemlock that have been dead just one year are modeled to lose only five percent of their merchantable volume to decay, regardless of bole or log size, based on the findings of Lowell and Cahill (1996).

REM 3.15.5. All other dead trees, including hem-fir trees dead more than one year, have estimates of their salvage volume and a tree volume computed from the species-specific equations developed by Czaplewski and others (1989) (see section 4.4.5.) set to zero. The number of logs from each salvage tree is determined by first subtracting the height of the butt log (equal to the stump height plus log length) from tree height. The number of logs above the butt log is estimated to be to the quotient of the length from butt log top to tree top divided by log length and rounded down to the closest integer. Total number of logs is the butt log plus the logs above the butt log.

For all other dead or cut trees, the Czaplewski equations determine statistically unbiased estimates of small-end diameters of logs sawn from trees. Total log volume is calculated using frustrum equations. Butt logs are calculated with greater weighting given to the top end diameter to account for taper. Logs higher up in the tree are calculated with equal weighting of top and bottom log diameters inside bark in the frustrum equations. Total tree merchantable volume is tallied with the variable **czvolume!**.

REM 3.15.6. For hem-fir species, timber volume for salvaged logs from trees dead more than one year is calculated with the equation in Lowell and Cahill (1996):

$RetainedVol = -9.99 + 336.06/DIB * (1.0 - CullFactor)$, where

RetainedVol = percent of volume lost to decay;

DIB = the diameter inside bark at the small end of a log; and

CullFactor = factor adjustment from a look-up table.

The cull factor is applied only if the time since death has been three years.

REM 3.15.7. Salvage volume from dead lodgepole pine dead for up to three years was calculated using data from a lumber mill recovery study from Wyoming (Fahey and others 1986, p. 17). The volume is derived from the equation:

$$\text{DeadLogMerchVol} = \text{LogMerchVol} * (-1.03 + 0.921 * \text{DeadLogProducts}) / (0.061 + 0.897 * \text{LiveLogProducts}),$$

where the variable DeadLogMerchVol is the merchantable volume of a live log times the ratio of chip and lumber products from dead logs divided by the chip and lumber products from live logs with equal volume. This equation applies to trees that have been dead two or three years.

REM 3.15.8. Salvage volumes from dead western white pines are calculated using combined equations from Snellgrove and Cahill (1980, class I and class II logs, equations for gross volume for lumber and chips, pp. 16 and 20). The equation for salvage volume is :

$$\text{DeadLogMerchVol} = \text{Yintercept} - 0.7119 * \text{LogDiameter} - 404.18/\text{LogDiameter} + 539.77/(\text{LogDiameter}^2),$$

where the variable DeadLogMerchVol is the merchantable volume of a dead log with a given top log diameter (the variable LogDiameter). If the tree has been dead one or two years, the value for Yintercept is 99.31. If the tree has been dead three years, the value for Yintercept is 93.28.

REM 3.15.9. The merchantable volume for a tree represented by a dead tree record is the sum of log volumes calculated with thousand cubic or thousand Scribner board foot volume (already reduced for defect), multiplied by the fraction of volume remaining after decay effects are accounted for.

REM 3.15.10. Whether alive or dead at the time of cutting, the merchantable timber volume from trees is added to the cumulative cubic sale volume in years with timber harvests or totaled to give a stand volume for standing timber in all years.

4.3.16. WEATHERDATA

Function - Introduce precipitation, solar radiation, and relative humidity data to simulate the effect of weather variables, their interception by forest canopy, and weather-induced changes in soil moisture and temperature
Model hypothesized production of pine mushrooms
Determine the feasibility of bough sales and Christmas tree sales based on road access, subject to snow on the ground

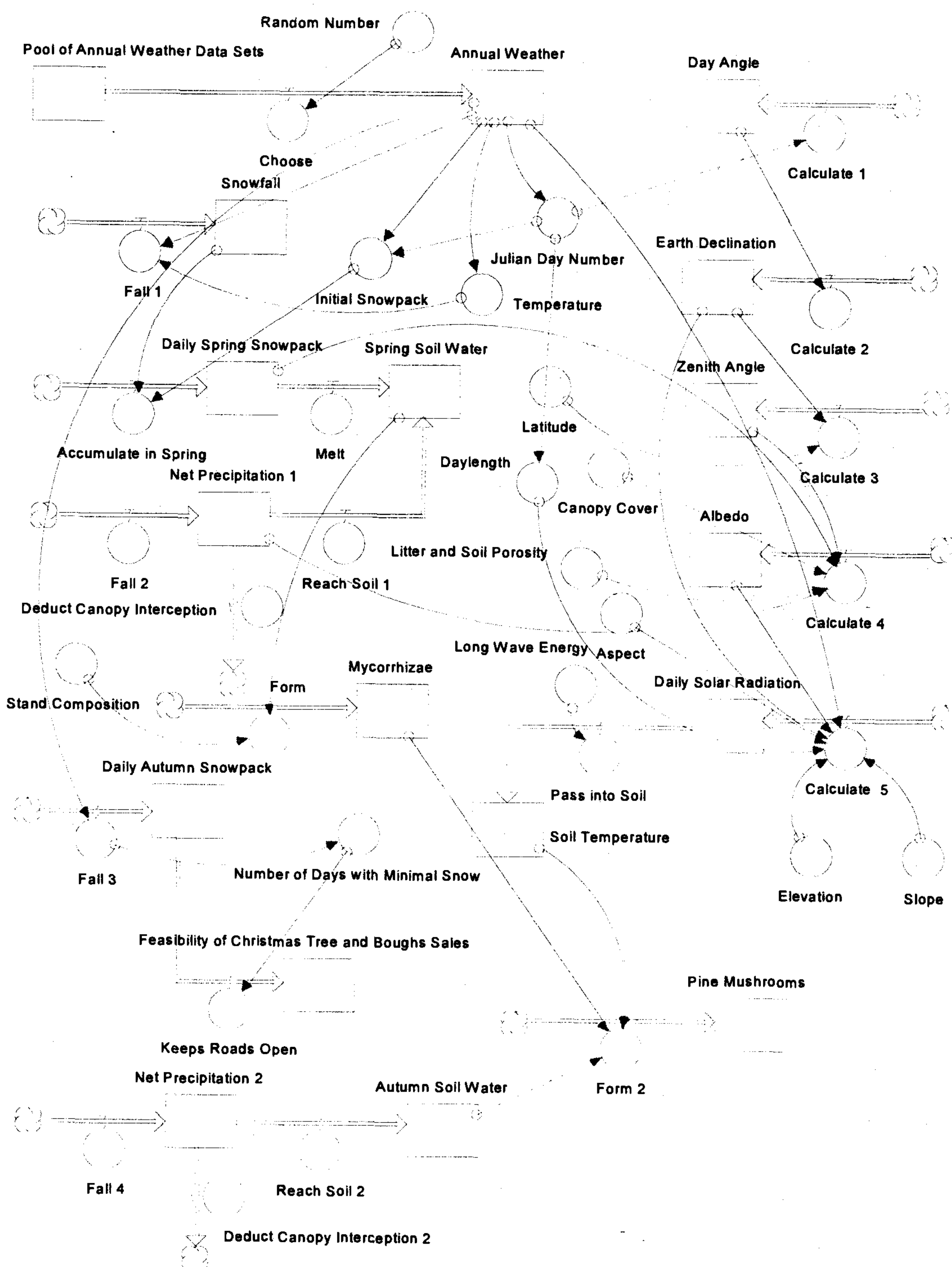
Variables Imported: A1waterfrac!, canopycover!, deltatemp!, leafareaindex!, litterdepth!, litterwaterfrac!, precip!, slope!, soiltemp!, soilwater!, tauo!, tfactor!, Tv!, year%

Variables Passed: stemareaindex!

Variables Exported: autumnsoilwater!, avtemp!, boughaccess%, canopycover!, day length!, declination!, deltatemp!, depth!, flushes%, julianday%, laststorm%, precip!, relhumid!, roadaccess!, shortwave!, snowpack!, solar!, xmasaccess%

With each annual call to WEATHERDATA, variables for the Julian day number, daily average temperature, daily total precipitation, snowpack depth, and solar radiation are read into the program. The Julian day number serves as the index variable and the remaining variables serve as array elements.

Figure 4.11. A schematic overview of WEATHERDATA.



REM 3.16.1. A random number is generated to select with equal probability one set of annual weather data stored in external files. Weather data consist of five array variables which are redimensioned when the subprogram opens. The five variables are average variables are a composite from three sources. All weather data except solar energy data are taken from databases maintained at the Natural Resource Conservation Service, Portland, OR. The weather station closest to the Diamond Lake pine mushroom management area is Lemolo Lake (station OR4835) at 43 degrees 22' N latitude, 122 degrees 13' W longitude, at an elevation of 1244 m (4080 ft). Weather data used in MUSHROOM may characterize an environment that is more sheltered and milder than the Diamond Lake pine mushroom management area. Eighteen years of data are available from the Lemolo Lake weather station. Three of the years, 1978, 1979, and 1992, however, have gaps in the data and are omitted from the model. All years are calculated with 365 days.

Daily relative humidity is registered generally at weather stations in agricultural areas. Data are taken from station OR24221 in Eugene, OR, the weather station closest to Diamond Lake west of the Cascade Crest. Observed incoming solar radiation comes from the H. J. Andrews Research Forest, Willamette National Forest.[3] The radiation expressed originally in langleys day^{-1}, has been converted to $J\ m^{-2}\ day^{-1}$ for use in MUSHROOM.

Diamond Lake site is 120 km south of the data collection site. Extrapolation of the data to the Diamond Lake site is likely a source of error. Insolation is higher, especially during the summer months, at Diamond Lake. The montane Mediterranean climate of the southern Cascade Range has some of the highest solar radiation in July in the continental

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[3]Solar radiation data sets were provided by the Forest Science Data Bank, a partnership between the Department of Forest Science, Oregon State University, and the U.S., Department of Agriculture, Forest Service, Pacific Northwest Research Station, Corvallis, OR.

United States (Gordon 1970). Correction for altitude but not latitude is incorporated into the program source code.

The variable **laststorm%** is linked to a particular set of weather data; **laststorm%** is the number of days since the last snowfall for day 80 (21 March) during the year from which the historical weather data are drawn.

REM 3.16.2. Variables to be calculated have their values set to zero. Spring and autumn amounts of water reaching the soil during the spring season (21 March to 21 June) and the amount of moisture reaching the soil and the soil temperature during the autumn season (25 August to 15 November (Julian days 238 to 345) are thought to be important to the phenology of pine mushrooms.

The number of days that roads are open to the management area during the commercial seasons for bough collection and Christmas tree cutting is set to zero. Feasibility of commercial harvest based on access to the set is set initially to "no" for each product. The variables **flushing%** and **seasonend%** mark the beginning and the end of fruiting season for pine mushrooms.

REM 3.16.3. Each day of the year between day 80 and day 345 is analyzed for inputs of water and energy into to the forest and, in particular, to the upper soil which pine mushroom mycelia inhabit. Winter snow pack on day 80 is divided by ten for approximate equivalent water depth and assigned to the variable **pack!**.

REM 3.16.4. Soil properties are introduced and given permanent values. Values are taken from or are calculated from a soil sample in the National Soil Data Bank near Lemolo Lake (see SOILENERGY, section 4.4.13.). Variables define the porosity of the A1 layer and average for organic litter as well as an average litter field capacity. On day 80, the soil and organic litter layers (if present) are assumed to be saturated with water.

Note: Ground is considered to have no effective organic layer if the average depth of the litter layer is less than 5 mm per unit land area.

REM 3.16.5. Zenith angle of the sun is an important variable for estimating the energy inputs to the forest site. It is computed in three steps. First, the day angle, expressed in radians and defined as the angle of the earth for a given day of a 365-day year (Iqbal 1983). The angle is calculated as:

$$DA = 2 * \pi * (JulianDay - 1)/365.$$

Then, the solar declination, the angle between the lines connecting the centers of the sun and the earth to the earth's equatorial plane, is calculated using the day angle (Iqbal 1983):

$$\delta = 0.006918 - 0.399912 * \cos(DA) + 0.070257 * \sin(DA) - 0.006758 * \cos(2 * DA) + 0.000907 * \sin(2 * DA) - 0.002697 * \cos(3 * DA) + 0.00148 * \sin(3 * DA),$$

where DA is the day angle and δ is the solar declination. The zenith angle specific to the day of the year and to the latitude is the difference between the latitude and the solar declination (Monteith and Unsworth 1990). The zenith angle estimates albedo using the method of Yin and Arp (1993). All angles are expressed in radians.

Note: The latitude of the Diamond Lake pine mushroom management area is 43°12' 7" N; the decimal equivalent is 43.2019 and is converted to radians and held as a constant value, specified in the core program.

REM 3.16.6. Albedo, the percentage of solar energy that is reflected back to space from the ground surface, is dependent on the type of ground surface. In this subprogram, albedo depends on the presence or absence of a snowpack and on the amount of moisture at the ground surface. The number of days since the last snow storm and the season affect the reflectivity of soil. Additions to the snowpack in the spring are modeled on daily precipitation and average daily temperature from the Lemolo Lake weather station. With each daily iteration, the variable snowfall is set back to zero. If there is precipitation from the Lemolo Lake data base and the average daily temperature falls below -1.1 °C, all precipitation falls as snow. Above 3.3° C, all precipitation is rain. In the transition phase between -1.1 and 3.3 °C, a weighted proportion of the precipitation falls as snow and as rain. The algorithm follows criteria used by Wigmosta and others (1994).

When the average depth of the snow pack is less than or equal to 0.5 cm, the pack is considered completely melted on a given day. A running tally is kept of the number of days since the last snowfall. The variable **laststorm%** is updated daily until the snowpack completely melts in the spring. Values for the number of days since the last snowfall affect measurement of snow albedo.

REM 3.16.7. When there is no snowpack, albedo is the function of the zenith angle and surface wetness. The procedure for determining daily albedo follows Pielke (1984). Albedo is calculated as follows:

$$\text{Albedo} = (\exp((\text{ZenithAngle}) * 180 * \pi)^{1.5} * 0.003286) - 1)/100 + \text{WetnessFactor} \quad \text{where,}$$

for ground with an organic litter layer:

if WaterPercent/Porosity ≤ 0.5 then
WetnessFactor = 0.14 *(1 − WaterPercent)/Porosity

if WaterPercent/Porosity > 0.5 then
WetnessFactor = 0.07

for ground without an organic litter layer:

if WaterPercent/Porosity ≤ 0.5 then
WetnessFactor = 0.31 − 0.34 *(1 − WaterPercent)/Porosity

if WaterPercent/Porosity > 0.5 then
WetnessFactor = 0.14.

All snow surfaces, whether under forest cover or in gap, are assumed to have the same albedo. Calculation of snow albedo follows Wigmosta and others (1994, equations 25a, 25b). Albedo is a function of the season as expressed by intervals of Julian days and the number of days since the last snow storm. The equations are:

for 1 *January* - 20 *March plus* 21 *September* - 31 *December*:

$$SnowAlbedo = 0.85 * (0.94^{LastStorm^{0.58}})$$

for 21 *March* - 20 *September*:

$$SnowAlbedo = 0.85 * (0.82^{LastStorm^{0.46}}),$$

where SnowAlbedo is the albedo from snow-covered surfaces and LastStorm is the number of days since the last storm.

The weighted average of stand albedo per unit area is the sum of the proportion of albedo from the area with canopy cover and the proportion of albedo from the area in gap space. Subtracting the albedo from the total incoming energy gives the amount of energy retained by the total forest surface area (the variable **tauo!**).

REM 3.16.8. Before a daily deduction of albedo is made, solar radiation for the day are adjusted to account for the increase in radiation with higher elevation. The process for correction requires several steps. First, the stand slope, equal to the tangent value, in percent is converted to a slope in radians. Then the hour angle, the angle between the south point and the rising (or setting) sun (Brock 1981) is calculated. Day length is derived by converting the hour angle to degrees and multiplying the arc cosine, expressed as radians, of the hour angle by 24/π (Monteith and Unsworth 1990).

Altitude adjustments follow algorithms created by Nikolov and Zeller (1992) and first calculate solar radiation from space, expressed in J cm^{-2} day^{-1}, with the equation:

$$Rad_{Space} = S_c * 458.37 * (1 + 0.033 * \cos(2 * \pi * JulianDay/365) * \cos(latitude) * \cos(declination) * \sin(HourAngle) + (HourAngle) * 180/\pi/57.296 * \sin(latitude) * \sin(declination))$$

The solar constant (S_c) has the value 8.238 J cm^{-2} min^{-1}, equivalent to 1.95 cal cm^{-2} min^{-1} (Gates 1980). The hour angle is the arc cosine of the product of the negative tangent of latitude times the tangent of the declination previously calculated in REM 3.16.5. Values for latitude, declination, and hour angle are all expressed in radians.

The following four equations are taken from algorithms by Nikolov and Zeller (1992). Estimates of solar energy at hourly intervals for a given Julian day are calculated to create a curve consisting of hourly points under which total solar energy for a day is integrated. A tilt factor is included by measuring the site aspect from the south for solar hourly incidence using the equation:

$$\text{Incidence} = \arccos(\sin(\text{latitude} - \text{slope}) * \sin(\text{declination}) + \cos(\text{latitude} - \text{slope}) * \cos(\text{declination}) * \cos(\text{HourAngle})$$

for directly south exposure and the following equation for sites having all other compass orientations and sloping terrain:

$$\text{Incidence} = \arccos(\text{Azimuth} - \text{Aspect}) * \cos(\text{SolarAngleElevation}) * \sin(\text{slope}) + \sin(\text{SolarAngleElevation}) * \cos(\text{slope}))$$

Reduced light attenuation through the atmosphere is corrected with the equation:

$$\text{Correction} = 1 - \exp(-k/\sin(\text{SolarElevation})) * (\text{elevation}_{\text{Diamond Lake}} - \text{elevation}_{\text{HJAndrews}})/\text{elevation}_{\text{HJAndrews}})$$

where k is the atmospheric radiation extinction coefficient, 586 J m^{-2} m^{-1}. The final adjustment of solar radiation from the H. J. Andrews Forest solar radiation data to approximate conditions at Diamond Lake is:

$$\text{Rad}_{\text{DiamondLake}} = \text{Rad}_{\text{HJAndrews}} + (\text{Rad}_{\text{Space}} - \text{Rad}_{\text{HJAndrews}} + 1) * \text{Correction}.$$

REM 3.16.9. Average daily temperature under the forest canopy (**Tc!**) is a function of the daily average temperature (Arp and Yin 1993):

$$T_c = -0.11 + 0.96 * \text{avtemp} - 0.00008 * \text{avtemp}^3$$

Temperature at the ground surface (**Tv!**) is calculated from Yin and Arp (1993) as a function of daily average temperature, the air temperature under the forest canopy, and value for leaf area index. If stand leaf area index is higher than 6.5, the effective leaf area index used is set at 6.5:

$$T_v = avtemp * (T_c - avtemp) * \ln(1 + min(maxLAI, standLAI) / \ln(1 + maxLAI).$$

REM 3.16.10. The amount of shortwave radiation is considered unaltered by a canopy extinction coefficient when the leaf area index or canopy cover is zero, that is, when there are no trees with dbh's larger than one inch. Light under the canopy is calculated with an equation from Sampson and Smith (1993) for unmanaged stands of lodgepole pine in Wyoming:

$$ShortWave = SolarRadiation * \exp(-((LAI^{-0.939} * Cover^{-0.292}) / \cos(ZenithAngle)) * LAI * 1.$$

This equation is useful because it is sensitive to leaf area index and gaps in canopy architecture; unfortunately, it does not account for other species. Its application to the Diamond Lake area is an extrapolation.

The forest canopy intercepts solar energy depending on the shape, depth, density distribution, and species composition of the canopy. Most data on canopy interception refer to single-species, even-aged stands. The stand structure at the Diamond Lake pine mushroom management area consists of multiple species and has an uneven age distribution. Until detailed and accurate data can be assembled about the site, modeling the amount of energy that reaches the ground under trees remains a weak link in the model.

Yin and Arp (1993, equation 13) measure long wave radiation for the site with:

$$LongWave = \sigma * ((AmbientTemp + 273)^4 - (TopLayerTemp + 273)^4) * 8.64 * 10^4$$

where σ is the Stefan-Boltzmann constant ($5.67 * 10^{-8}$ J m^{-2} s^{-1} K^{-4}). For use in the submodel, units for both short wave and long wave energy need to be figured as total solar radiation. The Sampson-Smith equation is adjusted from J m^{-2} s^{-1} to J m^{-2} day^{-1} by multiplying the equation by day length in hours times 3600. Long wave energy is measured in the Yin-Arp equation as a flux density in seconds that needs to be multiplied by $8.64*10^4$ to obtain the 24-hour total net long-wave radiation.

Total energy penetrating the ground, the variable **ras!**, is the sum of net long wave radiation plus short wave radiation.

REM 3.16.11. During the period of snow pack melt in the spring season (Julian days 80 through 172), the snowpack melts when the average daily temperature is greater than -2°C. An equation from Arp and Yin (1992, equation 3) predicts snow melt into the soil:

```
SnowMelt=0.5 *(Celsius +2.0) *Pack/30
```

where SnowMelt is the amount of water in centimeters that passes to the soil, and Pack is the water equivalent of the snow pack. The right-hand side of the equation is divided by thirty to estimate a daily melt rate from Arp and Yin's equation to predict monthly amounts of snow melt. On a daily basis, the melting amount is deducted from the stock of snow in **pack!**. Rainfall is assumed not to penetrate the snowpack to the soil and omitted from consideration until the snowpack disappears.

REM 3.16.12. When snow pack is absent, GASHCANOPY (section 4.4.7.) is called to predict the rainfall reaching the forest floor. A running tally using the variable **springsoilwater!** tracks the total amount of water passing into the soil during the spring season.

During the summer season, GASHCANOPY and SOILENERGY are called daily to model water passing into the soil and to estimate temperature in the A1 soil layer. Values for soil temperature and soil water are used as baseline values on Julian day 238 (August 25), from which time the season for pine mushroom fruiting is predicted.

REM 3.16.13. Scenario 12 in MUSHROOMYIELD (section 4.3.10.) predicts pine mushroom production based on hypothesized mechanisms by which water and soil temperatures affect the commercial production of pine mushrooms at the Diamond Lake management area. The mechanism reflects findings and observations about Asian pine mushroom production (Terashima and others 1995).

Volcanic pumice and ash soils in the region are poor conductors of heat (Cochran and others 1967). Although temperatures at the soil surface in open areas may reach as much as 65 to 70°C in the Cascade Range (Hallin 1967, Chen and others 1993), heat fluxes into the pumice and ash soils are much reduced because air, a poor conductor of heat, fills most of the pore space in the soil during the summer drought period. Soil temperature in late summer and early autumn is hypothesized to fall slowly unless there is rain. A pulse of water into the soil causes a drop in soil temperatures and also provides moisture for developing primordia into pine mushroom sporocarps.

The number of drops in soil temperature punctuated with stable or moderate increases in soil temperature as the soil dries between storms produces a flush of primordia and sporocarps approximately two weeks later. The number of flushes are tallied and are reported to MUSHROOMYIELD.

When scenario twelve is called to predict pine mushroom growth, a daily check is made to see whether the soil temperature has dropped below 2°C or if the snowpack exceeds 5 cm depth. If either event occurs, the commercial pine mushroom season ends. The value of the variable **seasonend%** becomes "yes." If these two events have yet to occur, GASHCANOPY and SOILENERGY continue to be called and a running tally is kept of the amount of water reaching the soil.

The number of flushes is tracked along with factors that presumably affect mushroom production. If no flushes have occurred thus far, then a flush first occurs with two events: the soil temperature lowers by three degrees and more than three centimeters of soil water enter the soil. Once environmental preconditions for flushing are met, several variables are initialized. A variable that tracks the amount of soil water flow since the initiation of a first flush is set to the amount of water entering the soil for the day when flushing begins. Net change in temperature is set to -3.0. Likewise, counter variables start tallying the number of dry days and wet days since flushing began. The process of **flushing%** has a "yes" value, and number of flushes begin to be counted.

When the variable **flushes%** has a positive value, net soil water and net change in temperature are tracked. When the ratio between net soil water input is greater than the water-holding capacity of the litter and A1 soil layers, the day is counted as a dry day. When there is no input of water to the soil, the day is declared a dry day. If the net temperature change since flushing rises by more than 2°C from one day to the next, a hot day is declared. If temperature falls by 2°C, a cold day is declared. If less than ten days have passed since flushing began, the sum of dry days, wet days, hot days, and cold days is tallied as **bad days%**, days unfavorable for pine mushroom development. If there are more than three such days, mushroom development aborts. The number of flushes is reduced by one and the process of waiting for conditions promoting a flush to begin again. If the number of days since flushing began reaches ten without bad days interrupting the process of sporocarp development, the flush is successful. All tallies of days are reset to zero.

After a successful flush, another flush may begin. The same conditions of soil temperature dropping by 3°C and a daily pulse of soil water equal to or greater than 1.5 cm trigger the flush. Otherwise, the variable **flushing%** has a "no" value and production is suspended. When favorable conditions reappear, the flushing% gets a "yes" value, the number of flushes is augmented by one, and bad days are counted once again.

REM 3.16.14. Weather data are used also to judge the feasibility of cropping other non-timber forest products: Christmas trees and ornamental boughs. The cropping season for boughs is set from October 15 to November 30, the season for Christmas trees from

November 15 to December 10. Access to harvest sites in the Diamond Lake area is constrained by snowpack. A fourteen-day window of access must be available in order to harvest boughs and Christmas trees commercially.

4.3.17. WOODSJOBS

Function - Calculate employment generated from stand management and product harvesting.

Variables Imported - boughmass!, conevalue!, lpconesperacre!, lpharvestrate!, mushroommass!, pileburning%, planting%, scraping%, scribnersalevolume!, totalcrop!, wpconesperacre!, wpharvestrate!, xmasvalue!

Variables Exported - jobs!

REM 3.17.1. In years when trees are harvested, the variable **scribnersalevolume!** has a positive value. That signal causes WOODSJOBS to calculate total timber volume harvested in units of thousands of Scribner board feet. The volume of timber cut is multiplied with the number of timber industry and Forest Service jobs that are generated by sale preparation, administrated, and product manufacture. Between 1955 and 1995, the number of jobs in Oregon generated from each thousand board feet of timber harvested has ranged widely from 0.0083 to 0.0156.[4] This model simplifies the historical record by assuming that each thousand board feet of timber creates 0.0117 of a full-time timber industry job each year. Employment in Forest Service creates an additional 0.0005 of a full-time job.[5]

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[4]Data on file at the U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

[5]Personal communication, 13 February 1997, Richard Haynes, research forester, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

Jobs created from planting trees, pileburning, and site preparation for natural regeneration are considered to require the same amount of labor as it takes to plant 450 trees per acre. Each activity creates 0.0023 of a full-time job. When the values of **planting%**, **scraping%**, or **pileburning%** have a value of "yes", the per-acre contribution to jobs is included for the current year. This figure assumes that an experienced tree planter plants 800 trees per day on near-level ground such as the Diamond Lake pine mushroom management area and that 450 trees per acre are planted on average.[6] Timber-related employment is the sum of Forest Service employment, contractor employment, and timber industry employment.

Note: A full-time job is assumed to consist of fifty weeks of labor per year at forty hours a week (Fight and others 1990). The number of hours of labor for each product group is divided by 2000 to give the product contribution to employment.

REM 3.17.2. Employment in bough production is based on an average daily production of 825 lbs (375 kg) of boughs (Ehlers 1970). The amount of commercial boughs obtained is divided by 825 to obtain the contribution to jobs in number of days consisting of eight hours. Annual contribution to employment then is the quotient of hours of labor and the number of labor hours per year, i.e. 2,000 hours.

Pine mushroom collection rates are based on observations by Miron (1994). Ten pounds per hour are assumed to be a single person's harvest rate in productive sites. Total annual production is divided by the hourly harvest rate and then by 2,000 for annual employment from pine mushrooms.

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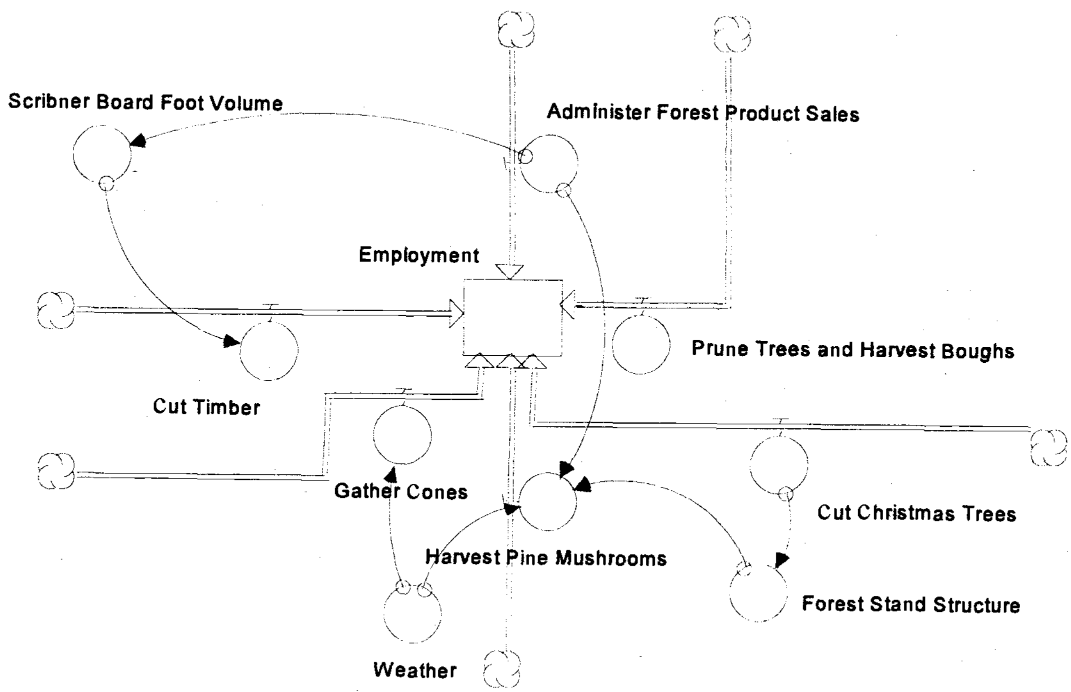
[6] Personal communications, 9 January 1997. Susan Willits, project leader, Pacific Northwest Research Station, Portland, and Susan Alexander, research forester, Pacific Northwest Research Station, Corvallis, OR.

Figure 4.12. A schematic overview of WOODSJOBS.



Christmas tree harvests are assumed to require one minute each for cutting and hauling each tree so that 30 trees per hour are harvested by one person. Employment through Christmas trees harvests per year is figured as the tree crop from one acre divided by the hourly rate divided by 2,000 hours labor per year.

REM 3.17.3. Daily production figures for pine cones in hectoliters come from Eremko and others (1989). The number of harvested western white pine cones per bushel (60) is assumed to equal figures for eastern white pine, and the number of cones per bushel of lodgepole pine (250) is assumed to be equal to ponderosa pine (U.S. Department of Agriculture 1948). The total bushel amount of commercial cones calculated per acre is multiplied by 0.352383, the factor conversion into hectoliters from bushels. Volume of cones in hectoliters is then divided by the number of hectoliters produced per day per person, i.e. 2.5 for western white pine and 0.7 for lodgepole and then divided by 250 workdays per year to get the percent of full employment contributed per acre per year from one acre of cone crops.

REM 3.17.4. The total portion of full-time employment generated from a single acre of forest from the Diamond Lake pine mushroom management area is the sum of jobs generated from producing timber, boughs, cones, pine mushrooms, and Christmas trees.

4.4. Documentation: Second-Level Subprograms

This section describes activities of the 18 second-level subprograms, that is, subprograms not directly called from the core program. The subprograms contain data sets, scenario models, statistical algorithms, or ecological processes invoked by one or more first-level subprograms, described in section 4.3, or by other second-level subprograms. Subprograms are arranged in alphabetical order and have annotative remarks in the same format used in sections 4.2. and 4.3.

4.4.1. BIGDIAMGROW

Function - Estimate diameter growth for trees with dbh's greater than three inches

Variables Imported: aspect!, barkratio!, batot!, crownratio!, dbh!, ddbh!, elevation!, functionnumber!, hgt!, normal!, pctile!, record%, relden!, siteindex!, slope!, species%

Variables Exported: dbh!, ddbh!

TREEGROWTH (section 4.3.14.) calls BIGDIAMGROW for each live tree record having a dbh larger than three inches. It incorporates features of the subroutines

DGBND.FOR, DGDRIV.FOR, and DGF.FOR from the Pacific Northwest Coast and West Cascades variants of the FVS (Donnelly 1995).

REM 4.1.1. The variable **scale%** is used to calculate an annual value from a decadal estimate for diameter and basal area growth of a tree.

The equation to determine the natural logarithm of the annual area increment for the inside-bark area is adapted from Johnson (1992). Species-specific empirical parameters estimate the natural logarithm of the annual area increment for the inside-bark area of trees at breast height. Parameter values are taken from (Johnson, 1992). Variables **b0!** and **b18!**, used in FVS, are omitted here because the five species modeled here all have zero values for those variables. Adding other species to the model may require including these variables.

The variable **balance!** is calculated as a relative value of dominance in the stand based on the percentile ranking by tree basal area. A high rank with a small amount of basal area from trees larger than a given tree produces a low value for **balance!** and reduces the effect of negative coefficients in the equation for calculating basal area growth.

The equation to calculate the decadal increment in inside-bark basal area takes the form:

$$\begin{aligned}\ln(BAI) = {} & b_1*\ln(SI)+b_2*\ln(TBA)+b_3*TBA+b_4*\ln(DBH)+b_5*CR+b_6*CR^2+b_7*BAL \\ & +b_8*ELE+b_9*ELE^2+b_{10}*\cos(ASP)*SL+b_{11}*\sin(ASP)*SL+b_{12}*SL+b_{13}*SL^2 \\ & +b_{14}*BAL/\ln(DBH+1)+b_{15}*RELD+b_{16}*DBH^2+b_{17}\end{aligned}$$

where ASP = stand directional aspect;

BAI = decadal basal area increment in square inches;

BAL = balance of stand basal area of trees with smaller dbh's than the current tree;

CR = tree crown ratio;

DBH = tree diameter at breast height in inches;

ELE = elevation in hundreds of feet;

RELD = species-specific relative stand density;

SI = the species-specific site index in feet;

SL = stand slope percent; and

TBA = total stand basal area in square feet.

For ease of comprehension, the equation is divided into five parts in the source code. Parameterization to local conditions has been omitted here.

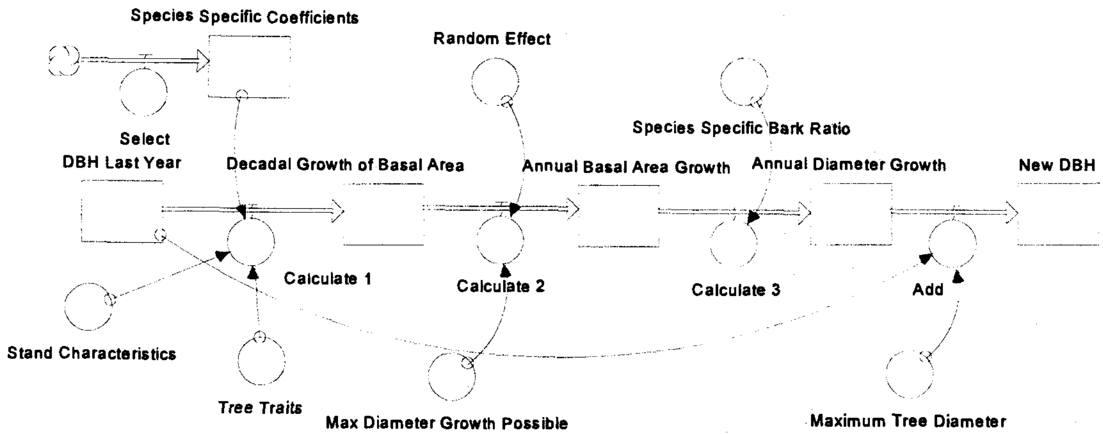
Computer code used is taken from Wykoff and others (1982, p. 53) and is a simplification of the code in the subroutine in the West Cascades variant of the FVS. The variable **dds!** is the estimate of the decadal increment to the inside-bark area for a tree record, the variable **dg!** is the decadal increment for the inside bark diameter. The value of **dib!**, the diameter inside bark, comes from multiplying the dbh (diameter outside bark by the bark ratio for a tree record. The first approximation for **dg!** is derived through the following steps:

1. The diameter inside bark for the record from the previous year, **dib!**, is squared;
2. The decadal increment of the inside-bark area is added the squared value in (1);
3. The square root of the value in (2) is obtained; and
4. The decadal diameter increment is obtained by subtracting **dib!** from the value obtained in (3).

REM 4.1.2. DISTRIBUTIONS (section 4.4.6.) provides a random variable from a normal distribution. The value is used to add a random component of no more than ten percent to the decadal diameter increment.

To preclude against unrealistically large increases in inside-bark diameter, three bounding conditions for decadal inside-bark diameter growth are set. First, the diameter growth

Figure 4.13. A schematic overview of BIGDIAMGROW.



increment cannot exceed the existing diameter in any year. Then, a maximum value for decadal diameter inside-bark growth increment is based on the previous year dbh and parameters for the maximum bounding function using Douglas-fir data and extrapolated to all other species. Last, any negative values for decadal inside-bark increment that might arise are reset to zero.

REM 4.1.3. The variable **olddbh!** holds the past year value for tree dbh during the following calculations. The annual value for inside-bark diameter increment, **treedib!**, is then determined by dividing the decadal value by **scale!**. This amount is added to the previous-year diameter inside bark to obtain the current-year diameter inside bark. The dbh value for the current year is derived by dividing the diameter inside bark by the bark ratio. Net increment in diameter outside bark is then obtained from the difference between the new value for dbh and the dbh from the previous year.

If the tree dbh exceeds the model limit of 150 inches, the dbh value is reset to 150, the dbh annual increment is set to zero for the year.

4.4.2. BIGHEIGHTGROW

Function - Estimate the annual height growth increment for trees with dbh's greater than three inches

Variables Imported: age%, avht40!, crownratio!, dbh!, ddbh!, dhgt!, hgt!, potentialheight!, record%, relden!, siteindex!,

Variables Exported: dhgt!, hgt!, maxhgtgrowth!

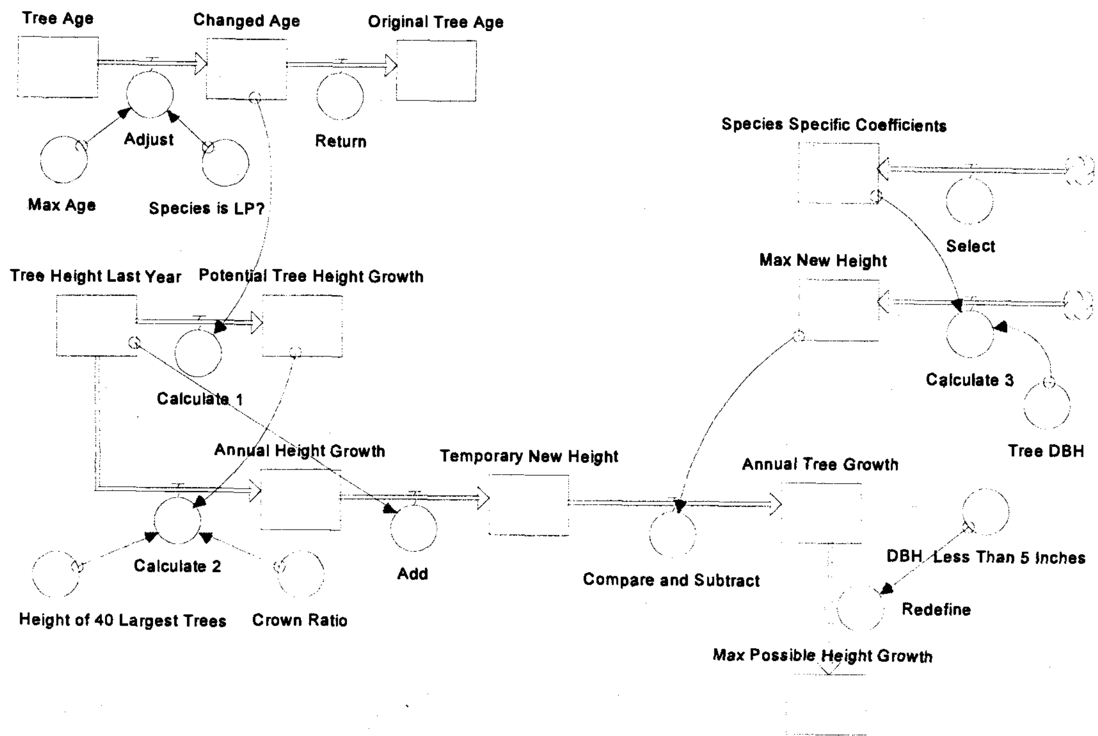
BIGHEIGHTGROW combines elements of the West Cascades variant of the FVS from the subroutines HTCALC, HTGF, SICHG, and SITSET. TREEGROWTH (section 4.3.14.) passes tree records with dbh's greater than three inches to BIGHEIGHTGROW to obtain an estimate of annual height growth increment.

REM 4.2.1. If the species for a tree record is lodgepole pine, five years are added to tree age. This change accommodates tree height estimates from Dahms' model (1964) that measures tree age from the tree base rather than at breast height.

Tree age has an upper limit at **agemax%** in FVS. The value of **agemax%** is a global constant and is set in the core program. Trees with ages exceeding the maximum allowable age have their ages set back to **agemax%**. TREEHEIGHT (section 4.4.14.) is called to give the potential height for a site tree of the same species and age as the tree record.

REM 4.2.2. If the tree record is lodgepole pine, the age for the tree record is lowered by five years to return the current age at breast height. The difference between the potential height derived from the call to TREEHEIGHT and the tree height from the previous year is calculated.

Figure 4.14. A schematic overview of BIGHEIGHTGROW.



REM 4.2.3. The relative height of the tree record is calculated from the ratio of the tree height to the average heights of the 40 trees with the largest dbh's from the previous year. If the average height of the 40 largest trees is zero because there are no trees in the stand taller than breast height, the relative height is set at zero. A relative height originally greater than one is set to one. The relative height and tree crown ratio are used in an empirical equation developed by Johnson (1992) to determine a height modifier. The equation has the form:

$$HeightModifier = 1.117148 * (1.0 - \exp(-4.26558 * CrownRatio)) * (\exp(2.54119 * (RelativeHeight^{0.250537} - 1)))$$

The product of the height modifier and the previously calculated potential height difference provides the first approximation for a height growth increment. A temporary new height is calculated with the first approximation of increment.

REM 4.2.4. An estimate of a height limit for the tree record is based on the dbh for the record and two species-specific empirical values. If the provisional new height exceeds the height limit, the height growth increment is equal to the difference between the height limit and unincremented tree height. A lower bound also limits the height growth increment to a minimum of 0.1 foot.

REM 4.2.5. If the current dbh value for the tree record is greater than or equal to five inches, the final estimate of the height growth increment is added to the height of the tree record in the previous year to give the current year height.

When the dbh for the tree record lies between three and five inches, the value of the height increment is returned to TREEHEIGHT as the maximum height growth possible. A lower limit is provided from SMALLHEIGHTGROW (section 4.4.12.).

4.4.3. CANOPYMASS

Function - Estimate the leaf area, leaf weight, and branch weight of a single tree from live tree records

Variables Imported: alive!, dbh!, hgt!, record%, species%, tpatot!

Variables Exported: branchmass!, foliararea!, foliarmass!

Information from CANOPYMASS serves two subprograms: for BOUGHS (section 4.3.2.), it estimates the amount of merchantable boughs derived from tree pruning; for LEAVES (section 4.3.9.), it furnishes data to compile the stand leaf area index and the amount of non-merchantable woody debris left after bough or whole tree harvests.

Each tree species is treated differently because the types of allometric information for the tree species are different. Many of the allometric equations used in CANOPYMASS come from a compilation by Means and others (1994).

REM 4.3.1. BOUGHS and LEAVES call only for live trees. Trees with less than one-inch diameters are excluded from calculations of canopy mass. By program definition, only trees with dbh's greater than one-inch are included as canopy trees. This generalization may lead to an underestimate of canopy mass and area, litter on the forest floor, and leaf area index. Allometric equations for tree canopy mass only extrapolate for trees with dbh's smaller than one inch.

In CANOPYMASS, measurements for stand and individual tree variables are first converted to metric amounts, except for some equations for western white pine. All weights are dry weights. The following metric variables are used: total number of trees per hectare, tree dbh in centimeters or meters, and tree height in meters.

REM 4.3.2. Equations used to describe canopy biomass are listed in table 4.3. by species. Specific leaf area data were calculated from samples taken at the Diamond Lake pine mushroom management area.

Equations for lodgepole pine are from Pearson and others (1984) for Rocky Mountain stands. Foliage and branch masses are a function of stand density and dbh of individual trees.

Western white pine equations are derived from Brown and others (1977), Brown (1978), and Snell and Brown (1978) for the Rocky Mountain and Intermountain regions. Except for Snell and Brown (1978), allometric equations are reckoned in English units and then converted from pounds into kilograms to conform with the calculations from the other model species.

There are no allometric equations available for Shasta red fir. Noble fir equations are surrogates for the two larger dbh classes. A regression of pooled *Abies* spp. (Gholz and others 1979) serves for the smallest dbh classes.

Allometric equations used for mountain hemlock rely also on equations from Pacific silver fir and western hemlock. Table 4.3. gives information about sources of substitution, in the absence of species-specific data.

REM 4.3.3. Branch mass for both living and dead branches, foliar mass, and foliar area are converted from metric units (kilograms, cubic meters, and square meters) to English units (pounds, cubic feet, and square feet). Values represent volumes, areas, and weights for a single tree from a tree record.

4.4.4. CROWNWIDTHS

Function - Estimate the crown widths of live trees
Variables Imported: dbh!, hgt!, record%, species%
Variables Exported: unprunedcrownwidth!

CROWNWIDTHS is called from BOUGHS (section 4.3.2.) and LEAVES (section 4.3.9.). The variables **big1**, **big2**, and **small!** presented here are elaborated from work by Donnelly at the U.S.D.A. Forest Management Service Center in Fort Collins, CO, to provide empirical equations to predict crown width from tree species in the Pacific Northwest. All unpruned tree crowns are assumed to be circular at their bases. These variables and their values are identical to those used in the West Cascades variant of the FVS.

Table 4.3. Allometric equations used in MUSHROOM for estimating canopy mass.

component	equation	range	sample size	r^2	source
Pacific silver fir - *Abies amabilis*					
foliage mass	$5.9 + 22.5 * (dbh / 100)^2 * height$	4.5 - 30.4 cm dbh 3.1 - 25.8 m height	n = 45	.54	Standish and others (1985)
foliage mass	$\exp(-4.5487 + 2.1926 * \ln(dbh))$	11.7 - 90.4 cm dbh	n = 9	.97	Gholz and others (1979)
live branch volume	$4.5 + 22.7 * (dbh / 100)^2 * height$	4.5 - 30.4 cm dbh 3.1 - 25.8 m height	n = 45	.53	Standish and others (1985)
live branch volume	$\exp(-5.237 + 2.6261 * \ln(dbh))$	11.7 - 90.4 cm dbh	n = 9	.96	Gholz and others (1979)
dead branch volume	$\exp(-7.0850 + 2.805 * \ln(dbh))$	not given	not given	not given	Harmon and others (1996)
Shasta red fir - *Abies magnifica* var. *shastensis* (using data from *A. amabilis* and *A. procera*)					
foliage mass	$5.9 + 22.5 * (dbh / 100)^2 * height$	4.5 - 30.4 cm dbh 3.1 - 25.8 m height	n = 45	.54	Standish and others (1985)
foliage mass	$\exp(-4.8728 + 2.1683 * \ln(dbh))$	18.8 - 111.0 cm dbh	n = 6	.99	Gholz and others (1979)
live branch volume	$4.5 + 22.7 * (dbh / 100)^2 * height$	4.5 - 30.4 cm dbh 3.1 - 25.8 m height	n = 45	.53	Standish and others (1985)
live branch volume	$\exp(-4.8287 + 2.5585 * \ln(dbh))$	18.8 - 111.0 cm dbh	n = 6	.94	Gholz and others (1979)

Table 4.3. continued.

dead branch volume	exp(- 7.0850 + 2.805 * ln(dbh))	not given	not given	not given	Harmon and others (1996)
lodgepole pine - *Pinus contorta* var. *murryana*					
foliage mass	exp(- 3.6187 + 1.8362 * ln(dbh))	2.5 - 28.7 cm dbh	n = 19	.84	Gholz and others (1979)
foliage mass	$10.3 + 0.016 * \pi * (dbh / 2)^2$	20 - 60 cm dbh < 1000 tph	not given	.91	Pearson and others (1984)
foliage mass	$- 1.0 + 0.034 * \pi * (dbh / 2)^2$	10 - 30 cm dbh 1000 - 1500 tph	not given	.83	Pearson and others (1984)
foliage mass	$- 0.5 + 0.031 * \pi * (dbh / 2)^2$	10 - 30 cm dbh 1500 - 2500 tph	not given	.84	Pearson and others (1984)
foliage mass	$- 0.14 + 0.025 * \pi * (dbh / 2)^2$	< 10 cm dbh > 9000 tph	not given	.84	Pearson and others (1984)
live branch mass	exp(- 4.6004 + 2.3533 * ln(dbh))	2.5 - 28.7 cm dbh	n = 19	.89	Gholz and others (1979)
live branch mass	$- 0.5 + 0.039 * \pi * (dbh / 2)^2$	10-60 cm dbh < 2500 tph	not given	.87	Pearson and others (1984)
live branch mass	$- 0.5 + 0.030 * \pi * (dbh / 2)^2$	< 10 cm dbh > 9000 tph	not given	.83	Pearson and others (1984)

Table 4.3. continued.

dead branch mass	exp(- 3.5290 + 1.7503 * ln(dbh))	not given	not given	not given	Harmon and others (1996)
western white pine - *Pinus monticola*					
[using English measurements, except as noted with ‡]					
foliage biomass	foliagepercent * (live crownweight + dead crownweight)	not given	not given	not given	Brown and others (1977)
foliage biomass	exp(- 1.1778 + 0.9197 * ln(dbh))	1.0 - 7.1 cm dbh	n = 5	.93	Snell and Brown (1978)
live crown weight ‡	0.3292 * height	< 2 inches dbh 1.6 - 13.1 feet	n = 13	.97	Brown (1978)
total branchwood	exp(- 1.3425 + 1.0232 * ln(dbh))	1.0 - 7.1 cm dbh	n = 5	.91	Snell and Brown (1979)
live crown weight	3.65 - 0.04534 * dbh^3 + 0.01233 * dbh^2 * height	1 - 43 inches	n = 44	.95	Brown (1978)
dead crown weight	exp(- 4.3970 + 2.6076 * ln(dbh))	1 - 25 inches	n = 18	.80	Brown (1978)
dead crown weight	(0.992 - 0.211 * ln(dbh)) * (22.46 + 0.0010 * x + 0.2425 * y) where x = 9.8^3 if dbh < = 9.8 or	1 - 80 inches	not given	not given	Snell and Brown (1980)

Table 4.3. continued.

	= dbh ^{3} if dbh > 9.8;				
	y = d ^{2} - 9.8 ^{2} if dbh <= 9.8 or				
	= 0 if d > 9.8				
mountain hemlock - *Tsuga mertensiana* (using equations in part for *Abies amabilis* and *Tsuga heterophylla*)					
foliage mass	5.9 + 22.5 * (dbh / 100) ^{2} * height	4.5 - 30.4 cm dbh 3.1 - 25.8 m height	n = 45	.54	Standish and others (1985)
foliage mass	4.1 + 9.1 * (dbh / 100) ^{2} * height	8.9 - 44 cm dbh	n = 39	.63	Standish and others (1985)
foliage mass	exp(- 3.8169 + 1.9756 * ln(dbh))	17.0 - 76.2 dbh	n = 11	.97	Gholz and others (1979)
live branch volume	4.5 + 22.7 * (dbh / 100) ^{2} * height	4.5 - 30.4 cm dbh 3.1 - 25.8 m height	n = 45	.53	Standish and others (1985)
live branch volume	4.2 + 17.4 * (dbh / 100) ^{2} * height	8.9 - 44 cm dbh	n = 39	.63	Standish and others (1985)
live branch volume	exp(- 5.2581 + 2.6045 * ln(dbh))	17.0 - 76.2	n = 11	.99	Gholz and others (1979)
dead branch volume	exp(- 7.0850 + 2.805 * ln(dbh))	not given	not given	not given	Harmon and others (1996)
dead branch volume	exp(- 9.9449 + 3.2845 * ln(dbh))	17.0 - 54.6 cm dbh	n = 6	.98	Gholz and others (1979)

REM 4.4.1. Regression equations predict crown widths for trees higher than breast height with the form:

$$CrownWidth = a * DBH^{b},$$

where a and b are empirical coefficients, **big1!** and **big2!**. Trees shorter than breast height have crown widths calculated from an equation of the form:

$$CrownWidth = a * TreeHeight,$$

where a is the variable **small!**.

Crown width extension for trees that have been pruned must be adjusted to account for shortened crown length. Crown width is reduced by pruning. The model assumes that a stand of pruned trees recovers from pruning and that pruned trees expand their pruned crown widths in years subsequent to pruning at rates equal to or higher than would an unpruned tree.

Limits to annual crown extension are placed on pruned trees. For pruned trees with dbh's larger than the variable **key1!**, annual crown width extension is set at a fixed rate of 10% until such time as the crown width of the pruned tree equals or slightly exceeds the crown width predicted by the Donnelly equations. Thereafter, the crown width of the pruned tree extends at the same rate as unpruned trees with the same dbh. Trees with dbh's included within the limits of **key2!** and **key1!** grow at a fixed annual rate of 20% until the dbh limit value set in **key1!** is reached.

4.4.5. CZAPLEWSKIEQUATIONS

Function - Estimate diameters inside bark at given tree heights from which estimates of log volumes can be made

Variables Imported: dbh!, hgt!, loghheightnow!, record%, species%

Variables Exported: unbiaseddib!

REM 4.5.1. The subprograms VOLUMECALC (section 4.3.15.) and PRUNINGPREMIUM (section 4.4.9.) make use of CZAPLEWSKIEQUATIONS. Equation parameters are selected to correspond with the species from the incoming tree record. Because parameters are not available for all species, some species use extrapolated parameters from similar species. Mountain hemlock is modelled as though it were Pacific silver fir. Western white pine is treated as though it were ponderosa pine.

REM 4.5.2. A regression equation system using species-specific parameters has been developed by Czaplewski and others (1989) to predict the diameter inside bark at a given height in the tree bole. The equation is best understood in component parts. First, a statistically biased estimate is generated for the diameter inside bark at a given height. The equation takes the form:

$$d_1 = D*((b_1*(h/H-1)+b_2*(h^2/H^2-1)+b_3*(a_1-h/H)^2*I_1+b_4*(a_2-h/H)^2*I_2)^{0.5},$$ where:

d_1 = biased estimate of diameter inside bark at a given tree height, in inches;

D = dbh (outside bark), inches;

h = tree height for predicting diameter inside bark;

H = total tree height;

$b_{1\text{-}4}$ = parameters for linear regression; and

$a_{1\text{-}2}$ = join points, where

$$I_i = \begin{cases} 1, & \text{if } h/H < a_i \\ 0, & \text{else} \end{cases}$$ where i=1, 2.

Better approximation of unbiased estimates is obtained by transforming d_1:

$$d_2 = d_1*(c_1+c_2*D+c_3*(D/H+c_4*h+c_5*h^2),$$ where

d_2 = unbiased estimate of diameter inside bark at a given tree height, in inches; and

$c_{1\text{-}5}$ = parameters for linear regression; and other variables are as before.

The value of the diameter inside bark at the specified log length (**logheightnow!**) on the tree is then returned to either as the variable **unbiaseddib!**

REM 4.5.3. Frequently the top log from a tree will have a small-end diameter less than four inches. If a small-end log diameter is less than the merchantable four-inch diameter width, the height of the log is iteratively shortened by six-inch increments until the diameter inside bark is equal to or slightly greater than four inches wide. A new statistically biased log top-end diameter inside bark is calculated and is returned to the originating subprogram.

4.4.6. DISTRIBUTIONS

Function - Generate random variables from beta and normal statistical distributions
Variables Imported: alpha!, beta!, functionnumber%
Variables Exported: betamultiplier!, normal!

REM 4.6.1. This subprogram provides randomly-generated variables for normal and beta statistical distributions: beta and normal to respond to calls for normally- and beta-distributed random numbers. The distribution requested is coded in the variable **functionnumber%**. A value of one signals a beta distribution, two signals a normal distribution. Both routines require a seed value supplied by RANDOMSHUFFLE to generate random variables. Algorithms are adapted from Press and others (1986).

The beta distribution uses a modified gamma distribution that requires input of alpha and beta parameters for the beta distribution being modelled. Calculation of the normally-distributed random number actually generates two variables after a call to RANDOMSHUFFLE (section 4.4.10.). A second random number from RANDOMSHUFFLE determines which of the two normally distributed random numbers is passed to subprogram requesting the random number generated from a normal distribution.

4.4.7. GASHCANOPY

Function - Estimate the amount of water reaching the soil from rain when there is no snow on the ground

Variables Imported: avtemp!, canopycover!, daylength!, declination!, julianday%, leafareaindex!, precip!, relhumid!, stemareaindex!, tauo!

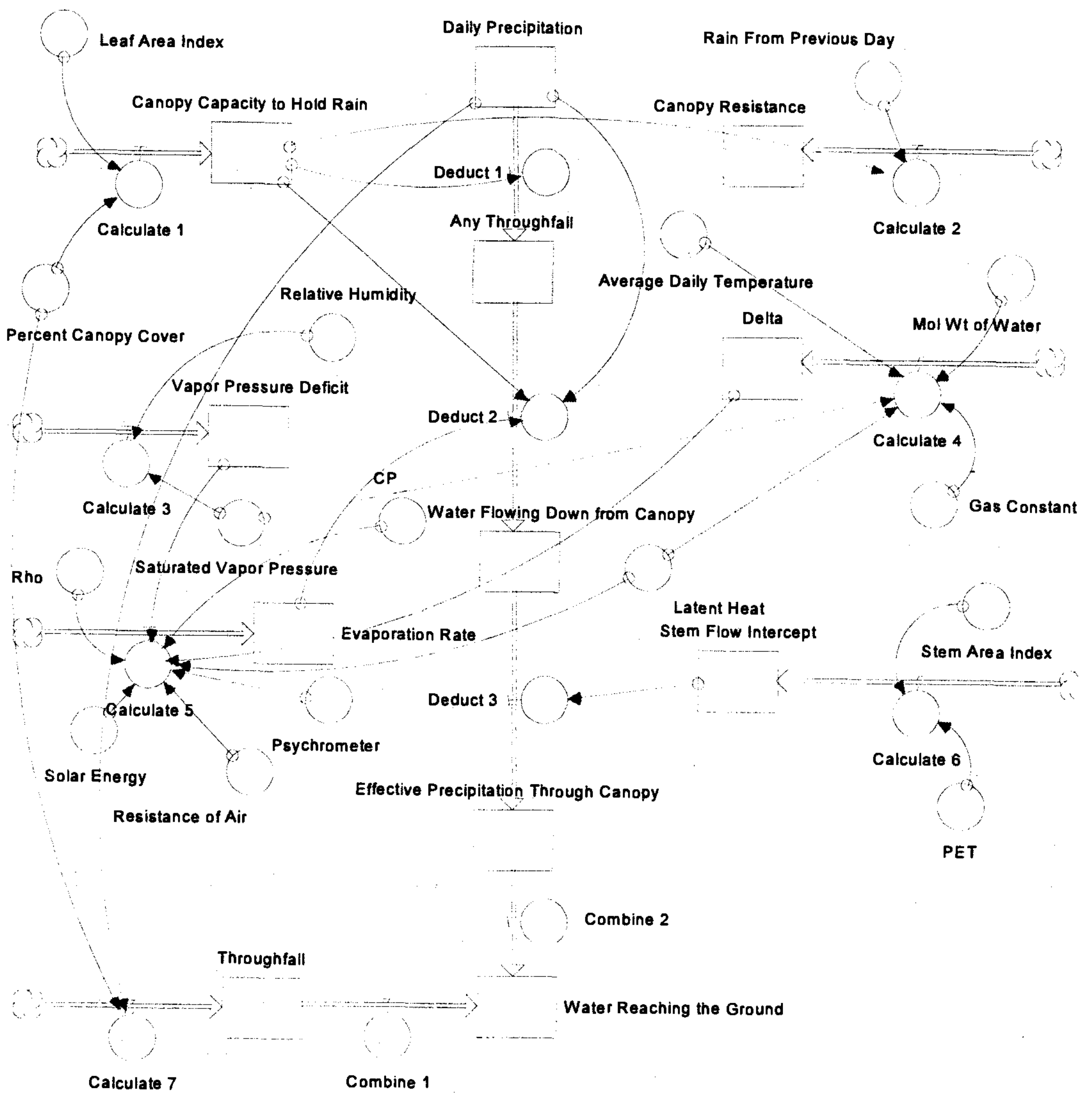
Variables Exported: soilwater!

WEATHERDATA calls this submodel for each day of the year for which information about rainwater entering the soil is needed. The two critical times are in the spring, when water availability is essential to tree growth during the short growing season, and in the autumn, when water is hypothesized to be critical to pine mushroom production. For more information about data sets imported to GASHCANOPY, see WEATHERDATA (section 4.3.16.).

For purposes of modelling, each day with precipitation is considered to have one storm. Pearce and Rowe (1981) describe errors in modeling results, however, when daily averages are used in place of hourly data. Hourly rainfall data have not been applied to the current version of the model. Also, adjustments to modelled results using canopy equations created by Gash and others (1995) are not included until field data on canopy interception are available from the Diamond Lake pine mushroom management area.

One important simplifying assumption in the model is that trees with dbh's less than one inch do not impede water from reaching the forest floor.

Figure 4.15. A schematic overview of GASHCANOPY.



REM 4.7.1. The variable **soilwater!** is the daily amount of water entering the soil when there is no snow on the ground or in trees. The equations derive in part from Gash (1979) and Gash and others (1995).

REM 4.7.2. Average hourly rainfall rates are unknown at the Diamond Lake pine mushroom management area. Studies that have tracked average hourly rainfall rates to validate the Gash canopy model show average rainfall rates ranging from 1.22 to 1.85 mm per hour (Gash 1979; Gash, Wright, and Lloyd 1980; Pearce and Rowe 1981; Loustau and others 1992; Gash and others 1995). Probability distributions of rainfall rates are not provided. The variable **rbar!** represents here a daily rainfall rate and is the daily precipitation data from Lemolo Lake.

Canopy resistance varies during the course of a day but an average resistance value of 125 sec m^{-1} on dry days is assumed here. On many days the average canopy resistance lowers depending on the weather of the previous day. If the previous day has had rainfall that wets the canopy, canopy resistance may drop to 12.5 sec m^{-1}. A previously wetted canopy will have already absorbed the quantity of precipitation represented by the value of the variable **Sc!**. The value for aerodynamic resistance to vapor transport (**ra!**) is given a fixed value, 2.5 sec m^{-1}, to conform with a standard ratio value for **rc!/ra!** equal to 50 under dry conditions (Monteith and Unsworth 1990).

REM 4.7.3. The Penman-Monteith equation is used to calculate evaporation of water from the wetted canopy (Kelliher and Black 1986, Wigmosta and others 1994). Elements of the equation are first calculated. All average daily temperatures are converted to degrees Kelvin. Latent heat of vaporization in units of J g^{-1} follows the regression:

$$\lambda = 3148.8 - 0.002.3756 * Kelvin$$

for the range -5 to 45°C. The density of moist air (ρ) in units of g m^{-3} and the "psychrometer constant" (γ) in units of kPa K^{-1} are also calculated with regressions based on data given (Monteith and Unsworth 1990, table A.3). Respective equations are:

$\rho = 2410.1 - 4.1028 * Kelvin$ and $\gamma = 0.047228 + 6.3655 * 10^{-5} * Kelvin$.

Saturated vapor pressure ($e_{s(T)}$) in kPa for a given Kelvin temperature (T) is estimated empirically using the method of Murray cited in Monteith and Unsworth (1990, equation 2.23):

$$e_{s(T)} = e_{s(273K)} * \exp(17.27 * (T - 273)/(T - 36)), \text{ where } e_{s(273K)} = 0.611 \text{ kPa}.$$

The variable Δ represents the slope of the saturated vapor pressure/temperature curve ($\delta e_{s(T)}/\delta T$), and is empirically calculated as the product of the temperature-specific value for latent heat times the molecular weight of water times the temperature-specific saturated vapor pressure divided by the gas constant and by the Kelvin temperature squared. Actual average daily air vapor pressure is derived by multiplying the average daily relative humidity is imported from WEATHERDATA.

The Penman-Monteith equation takes the form:

$$\overline{E}_c = \frac{\Delta * \tau_o + \rho * c_p * (VPD)/r_a}{\lambda * (\Delta + \gamma(1 + r_c/r_a))} dt,$$ where $\overline{E}_c$ is the rate of water evaporation from the

canopy surface expressed in g m^{-2} sec^{-1}. Remaining variables are as defined above or as follows:

τ_o = net radiation flux density in J m^{-2} sec^{-1};

c_p = specific heat of air at constant pressure, assumed constant at 1.050 J g^{-1} K^{-1}; and

VPD = vapor pressure deficit, the difference between the saturated vapor pressure and the daily average vapor pressure in kPa.

The elevation-adjusted shortwave daily flux density calculated in WEATHERDATA has units in J m^{-2} day^{-1}. Converting the Penman-Monteith equation to units comparable with the daily solar radiation data for generating an average daily $\overline{E}_c$ requires that the second term in the numerator $\rho * c_p * (VPD)/r_a$, in net units of J *kPa°K^{-1} m^{-2} sec^{-1}, be multiplied by 8.64 x 10^4.

REM 4.7.4. Stem area index is the basis for calculating interception of rain by tree stems and branches. The method for calculating stem and branch interception follows the method of Arp and Yin (1992). Stem density index is previously calculated in LEAVES (section 4.3.9.) and passed to GASHCANOPY by way of WEATHERDATA.

Daily stem interception is proportional to the amount of rainfall or to the daily maximum potential evaporation rate (PET), whichever is less. Three elements are needed to estimate PET: saturated water vapor density (ρ) in units of g m^{-3} for the average daily temperature, daylength as calculated for each Julian day in WEATHERDATA and divided by 2, and an empirical calibration assumed here as in Arp and Yin (1992) to be 0.025. Units for stem evaporation are g m^{-2} day^{-1}. To obtain the daily rate per square centimeter, the value of stem evaporation is then multiplied by 10^{-4} to keep consistent units with evaporation and rainfall rates.

The daily rainfall amount is compared to PET to see which value is less. Stemflow interception is then calculated with the equation (Arp and Yin 1992):

$$StemInterception = 0.025 * StemAreaIndex * \min(PET, Precip),$$ where

PET = potential evapotranspiration g cm^{-2} day^{-1}; and

Precip = precipitation recorded from Lemolo Lake as cm day^{-1}.

REM 4.7.5. The model redefines the equation by Gash and others (1995) to estimate the rainfall necessary to saturate the canopy as:

$$P_G = -\frac{\overline{R} * S_c}{\overline{E}_c} * \ln\left[1 - \frac{\overline{E}_c}{\overline{R}}\right]$$

where P_G = the rainfall necessary to saturate the canopied portion of the site;

$\overline{R}$ = the mean rainfall rate per day;

S_c = the canopy capacity per unit area of canopy cover; and

$\overline{E}_c$ = the mean evaporation rate per day.

If the daily rainfall does not exceed the rainfall necessary for canopy saturation, the effective rainfall under the canopy remains at zero. If a surplus of rainfall exists after rain wets the canopy, other deductions are made for evaporation from the saturated canopy until the rainfall ceases, that is, net deductions equal to $\bar{E}_c/\bar{R}$ for the daily duration of the storm after initial canopy wetting, and for daily evaporation from stems and branches.

REM 4.7.6. After deductions are made for canopy interception, the total effective precipitation is estimated. In forest gaps, the effective rainfall is equal to the precipitation. The weighted sum of precipitation falling directly to the soil in gaps (assuming here that small trees and sparse shrubs do not intercept water significantly) and the precipitation not permanently intercepted by the canopy and reaching the forest floor constitutes daily precipitation effectively reaching the ground.

Note: This model does not account for canopy interception of fog. Trees with dbh's less than one inch are not calculated in the canopy storage variable **Sc!**. Evaporation from the forest floor and open areas also is omitted from the model in its present form. The high soil porosity is assumed to have infinite capacity to absorb water (see SOILENERGY, section 4.4.13.).

4.4.8. MUSHROOMPRICES

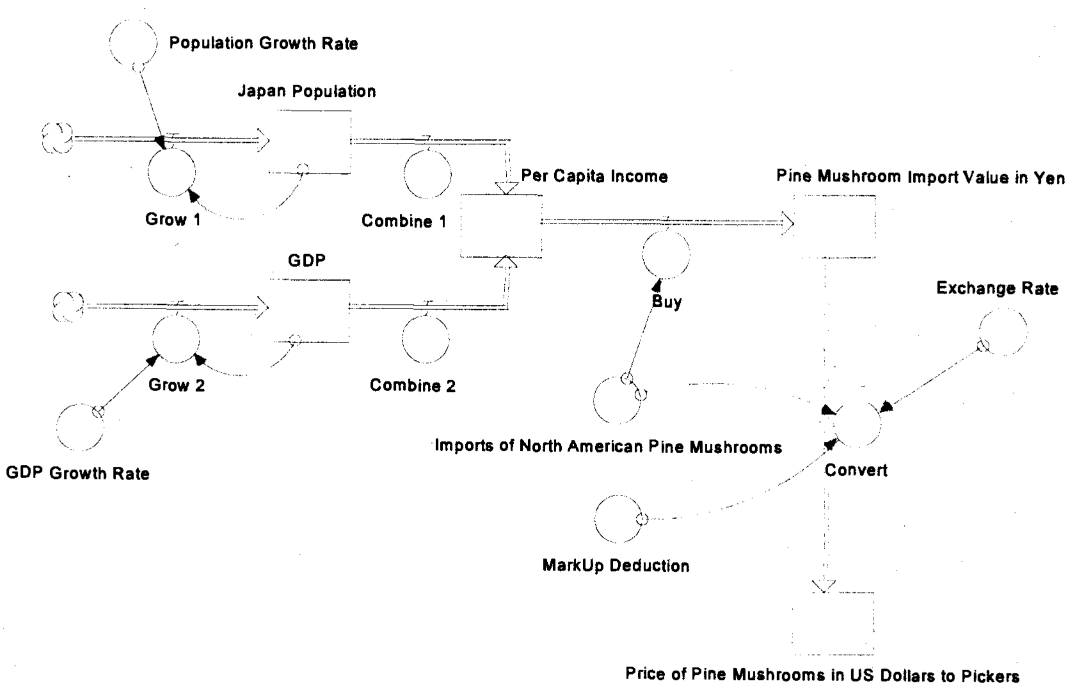
Function - Estimate an average annual price for pine mushrooms in constant 1990 U.S. dollars per kilogram of fresh weight

Variables Imported: calendaryear%, management%, mushroompricescenario%, year%

Variables Exported: mushroomprice!

REM 4.8.1. Three variables, **exchange!**, **gdp!**, and **population!**, are made static variables so that their values are retained between annual calls to MUSHROOMPRICES.

Figure 4.16. A schematic overview of MUSHROOMPRICES.



The core program specifies the scenario in MUSHROOMPRICES used to forecast the annual growth rate of the gross domestic product (GDP) in Japan for the period 1996-2020. Each scenario is designed to test the financial sensitivity of future pine mushroom prices to economic conditions in Japan, the major market for pine mushrooms. Four choices are available:

- a constant Japan GDP, based on the 1995 Japan GDP, for the period 1996-2020;
- Japan GDP increasing at an annual rate of 1.5 percent, representing actual growth for the years 1992 to 1995;
- Japan GDP increasing at an annual rate of 5.5 percent, representing actual growth for the years 1976 to 1995; and
- Japan GDP increasing at an annual rate of 6.5 percent, representing actual growth for the year 1976-1991.

REM 4.8.2. Per capita income provides an index of disposable income available to Japanese consumers. Income is derived by dividing the projected GDP by the projected population. The same population projection is used for all four GDP scenarios. Population projection for the period 1996-2020 follows the same declining rate of population increase growth characteristic of the period 1976-1995. The exponential rate of population increase is expressed as:

1.0112 - 0.0028177 * ln (calendar year - 1975)

Population in a given year is the product of the population from the previous year times the year-specific population growth rate calculated from the equation above. The Japan GDP for a particular year is the product of the previous year GDP times the GDP growth rate selected for the mushroom price scenario.

Per capita income is then derived by dividing Japan GDP for a given year by the population projected for the same year.

REM 4.8.3. Projected annual production figures for North American pine mushrooms are modeled after actual production quantities for North American exports to Japan for the period 1986-1995 (Weigand 1997c). Each annual figure has an equal probability of being chosen in any given future year. The ten-year production series was chosen instead of the 20-year production record available because of the "start-up" nature of the industry from 1976 to 1985. Production figures were low in early years while the export trade in pine mushrooms from North America was just beginning.

REM 4.8.4. A choice of scenarios is available to reflect possible trends for intensifying management for pine mushrooms in North America. Three scenarios are envisioned. The first scenario assumes that widespread management for pine mushrooms is not undertaken. Crops for the most part continue to be harvested from forests that are not consciously managed to augment production of pine mushrooms. Management scenario two assumes that within five years, the first benefits of pine mushroom production appear regionally. Measures such as those implemented at the Diamond Lake pine mushroom management area double on average pine mushroom production under unmanaged conditions. In the third scenario, even greater intensification of management to promote pine mushroom production assumes that within ten years, pine mushroom production from North America will be five times greater than production recorded from 1986 to 1995. Under the latter scenario, production in North America would approach the quantity of current production in the Republic of Korea.

REM 4.8.5. The average price per kilogram of pine mushrooms harvested in North America on arrival in Japan for any given future year is expressed in constant 1990 Japanese yen. The equation to predict price is taken from a regression equation relating North American production to the Japanese market in Weigand (1997c). The equation is inverted so that price is forecast with values already specified of quantity produced in North America and Japan per capita income. North American production in these cases is assumed to equal Japan demand. The equation takes the form:

$$YenPrice = \exp((-34.058 - \ln(NAproduction) - 7.8684 * \ln(JapanIncome))/2.9368) * 10,$$

where: YenPrice = the price per kilogram of North American pine mushrooms in constant 1990 Japanese yen;

NAproduction = the production quantity of North American pine mushrooms exported to Japan; and

JapanIncome = the per capita income forecast for Japan.

REM 4.8.6. Conversion of the yen price to a dollar price requires using one of twenty randomly chosen exchange rates. Each possible exchange rate is an average annual exchange rate for Japanese yen per U.S. dollar during the period 1976-1995. The exchange rate for 1995 (year zero) is pegged at the actual average value recorded in 1995 - 93.96 yen to the dollar (Office of the President 1996).

REM 4.8.7. The value of pine mushrooms to harvesters is comparable to a stumpage price for timber. To calculate the value of pine mushrooms to harvesters in North America from arrival prices to Japanese distributors, the mushroom price in yen is divided by the randomly chosen yen-to-dollar exchange rate. Shipping costs per kilogram are then deducted. Costs in U.S. dollars are based on figures from Meyer Resources Inc. (1995), originally expressed in Canadian dollars. To account for distributors' markups, the residual price is then multiplied by 0.3 to arrive at the price paid to pickers.

The mushroom price developed in this subprogram is then forwarded to MUSHROOMYIELD (section 4.3.10.) to calculate the annual per acre crop value from the Diamond Lake pine mushroom management area.

4.4.9. PRUNINGPREMIUM

Function - Assess a premium in value added to lumber that comes from trees with previously pruned butt logs

Variables Imported: dbh!, hgt!, logheightnow!, record%, species%, unbiaseddib!

Variables Exported: logheightnow!, prunedportion!

Little information is available at present that connects production outputs resulting from pruning practices of the species considered in this model. Most research about the effects of pruning on timber quality concerns Douglas-fir and ponderosa pine (Fight and others 1992a, b), both species which dominate lumber production in the Pacific Northwest. O'Hara and others underscore the multiple benefits of pruning western white pine in particular (1995b). Production functions for increased volume and value from improved timber quality through pruning have to be inferred in most cases. Cahill (1991) provides some data for the increase in volume and value of lumber production for Douglas-fir and ponderosa pine. His findings serve to model financial effects of pruning in WOODUSE (section 4.4.17.).

REM 4.9.1. Two local arrays are established to hold values of the top-end diamters inside bark for trees and their respective log heights.

Trees pruned to 17.5 feet have a **prune%** value equal to three and produce a sixteen-foot butt log with better quality, knot-free wood. The top diameter of log at the height limit of pruning, 17.5 feet, is calculated with a call to CZAPLEWSKIEQUATIONS (section 4.4.5.). The diameter inside bark of the stump is also calculated to furnish the basal area of the butt log as is frustrum volume of the butt log to 17.5 feet. Merchantable volume from the pruned tree above the 17.5 feet is then interatively estimated until the top-end inside diameter equals or is less than the minimum merchantable top-end diameter, set at four inches in the core program. The percentage of the tree bole that consists of wood from the pruned stem is calculated by dividing the pruned log volume by the total wood volume of the tree.

4.4.10. RANDOMSHUFFLE

Function: Reshuffle numbers produced by the QBasic random number generator to ensure true statistical randomness.

Variables Imported: xyz%

Variables Exported: RANDOMSHUFFLE!(xyz%)

REM 4.10.1. The algorithm is modified from Press (1986). In each simulation run, a random number is generated with the RANDOMIZE TIMER function in the core program. The random number is multiplied by -1. The negative value is passed to RANDOMSHUFFLE.

A local array **v!** is established and remains static through the course of each planning cycle. The array holds a set of 97 random numbers. The variable **iff%** is also included in the event of faulty application of RANDOMSHUFFLE to block the function operation.

REM 4.10.2. The first time RANDOMSHUFFLE is called in a simulation cycle run, the negative value of **xyz%** initiates a one-time process to generate a pseudo-random series of numbers. The absolute value of **xyz%** initiates a series of 97 random numbers beginning with the 98th number from the random number stack generated by the random-number routine in the computer software.

REM 4.10.3. A 185th number from the same stack of random numbers is transformed into the integer value representing the place in the array stack from which a random number will be drawn after the array stack is reinitialized.

REM 4.10.4. In the event that an extralimital value for an array pointer appears in the routine, an error message is printed in the output file.

REM 4.10.5. The randomly-selected number from the current array of 97 randomly-generated numbers is assigned as the value of RANDOMSHUFFLE. The number is between 0.0 and 1.0. A new QBasic random number is generated and replaces in the array stack the random number just removed.

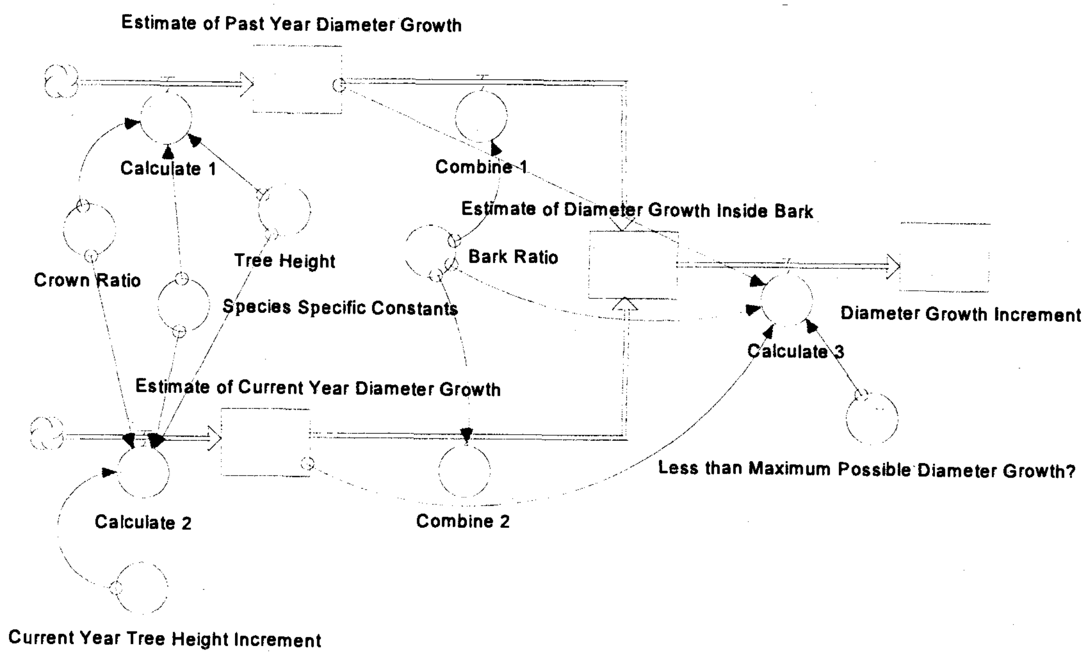
4.4.11. SMALLDIAMGROW

Function - Estimate diameter growth for trees taller than breast height and with dbh's less than three inches

Variables Imported: barkratio!, crownratio!, dhgt!, hgt!, record%, species%

Variables Exported: dbh!, ddbh!

Figure 4.17. A schematic overview of SMALLDIAMGROW.



The algorithm for diameter growth for trees with dbh's greater than zero and less than three inches is adapted from the subroutine REGENT in the West Cascade variant of the FVS. This subprogram is called from TREEGROWTH.

REM 4.11.1. The appropriate time scale and maximum diameter growth for small trees are set. A small tree can have no more than one inch of annual diameter growth. Three species-specific parameters for regression equations are assigned. Lodgepole pine and western white pine are modeled with the identical parameters.

REM 4.11.2. The empirically-derived equation for predicting the diameter of small trees takes the form:

Diameter=(a+b*CR+c*ln(Height)),

where CR is the closest integer value of ten times the decimal fraction of crown ratio. At the same time, a second equation calculates a tree diameter as though the tree were to grow by the same height increment as in the previous year. Bounds are set for each estimate so that estimates have positive values. In the case of negative values, the increment in tree height based on the existing **dhgt!** value is multiplied by 0.2 times the current bark ratio. The first approximation of diameter growth inside bark, **dg!**, is set as the difference of the two diameters times the tree bark ratio at dbh. Upper and lower bounds are set so that the diameter growth is positive and lies between 0.01 and the maximum diameter growth set by **dgmax!**. The basal area increment inside bark, **dds!** and its square root are calculated to obtain the annual diameter increment inside bark. The amount is divided by the bark ratio to get the diameter increment including bark. Adding the new **ddbh!** value to the past year **dbh!** results in the current year **dbh!** value.

4.4.12. SMALLHEIGHTGROW

Function - Estimate the height increment and current year height of trees with dbh's greater than zero and less than five inches

Variables Imported: batot!, crownratio!, dbh!, normal!, record%, relden!

Variables Passed: alpha!, beta!, betamultiplier!, functionnumber%,

Variables Exported: dhgt!, hgt!, minhtgrowth!

SMALLHEIGHTGROW is adapted from the subroutine REGENT in the West Cascade version of the FVS. Dbh's of small trees are calculated before their heights.

REM 4.12.1. The subprogram calculates the height growth increment of a tree over a decade. The variable **scale!** reduces the height projection to an annual amout.

REM 4.12.2. A maximum possible decadal height growth increment is based on the relative density of the stand and takes the equation form:

PotentialHeightGrowth = 10.2 − 0.03 * RelativeStandDensity

Relative stand density is previously calculated in LEAVES (section 4.3.9.).

A series of calculations creates a modifier variable that reduces the potential height growth to reflect the stand density expressed in basal area of trees at dbh. Stand density is assumed to reduce height growth in small trees. The threshold stand density affecting tree height growth depends on the dbh of the respective tree. Stand basal area assumed to limit growth of trees with dbh's of between two and five inches is 280 sq ft. Trees between one-half and two inches have growth limited where stands have a basal area greater than 280 times the tree radius at breast height. Trees less than one-half inch will not grow in stand conditions where the basal area is greater than 70 sq ft.

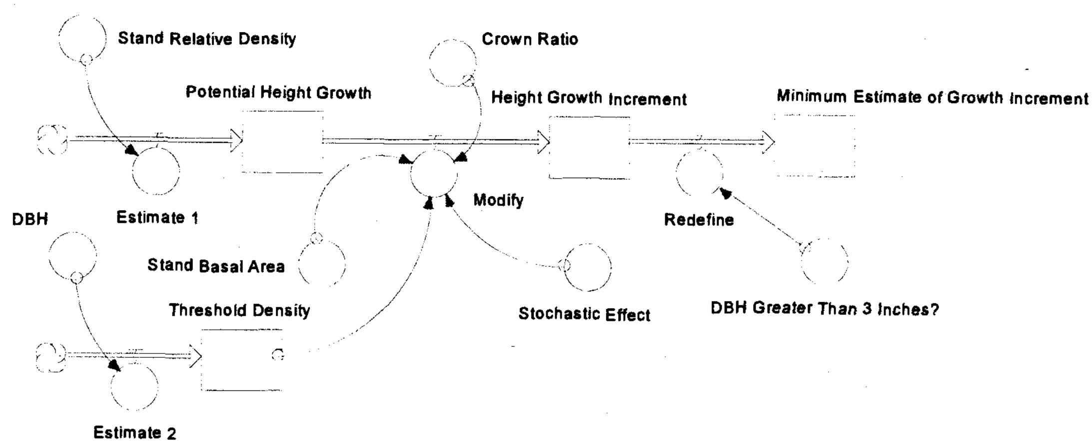
The limit to growth of small trees is set at the threshhold stand basal area minus one square foot. If the current stand basal area is less than or equal to the growth limit, the growth limit is set to the current basal area. If the limit to tree growth should happen to be less than one foot, then the limit is bounded from below at one.

REM 4.12.3. The crown ratio of the current tree record, expressed as a decimal fraction, is multiplied by 10 and rounded to the nearest single digit integer on a scale between zero and nine. For example, a tree record with a current crown ratio of 0.48 would be multiplied by 10 for a value of 4.8 and rounded to a value of 5. Together with the appropriate limiting stand density, the growth limit, and the crown ratio code, a modifier to potential small tree growth is derived with the equation form:

$\text{Modifier} = (1.0 - \exp^{(-2.0 * (\text{StandDensityLimit} - \text{StandBasalArea}) / \text{StandBasalArea})}) * \text{CrownCode} * 0.12.$

The estimate of height growth is multiplied by the density-based modifier. A call to

Figure 4.18. A schematic overview of SMALLHEIGHTGROW.



DISTRIBUTIONS (section 4.4.6.) provides a random variable from a normal distribution and the number is multiplied by 0.1 for the decadal tree height increment. The scale variable reduces the estimate to an annual year estimate.

REM 4.12.4. If the tree has a current dbh less than three inches, the height estimate is automatically assigned as the height growth increment for the current year. The height growth increment is then added directly to the past-year height to give the total tree current-year height.

If the current-year value for dbh lies between three and five inches, the height increment value is sent to TREEGROWTH to contribute to a weighted average for tree height growth with the estimate from BIGHEIGHTGROW (section 4.4.2.). The contribution of small tree height increment is held in the variable **minhtgrowth!**.

4.4.13. SOILENERGY

Function - Model the transfer of heat and movement of water from the ground surface through the upper soil where mycelia, mycorrhizae, and fruiting bodies of pine mushrooms concentrate

Variables Imported: A1waterfrac!, avtemp!, julianday%, laststorm%, leafareaindex!, litterwaterfrac!, ras!, shortwave!, soilwater!, solar!, Tv!

Variables Exported: deltatemp!, soiltemp!, tfactor!

Modelling energy flows applies discretization equations using a tridiagonal matrix algorithm (Pantankar 1980) for heat transfer. One-dimensional conduction is assumed, and within each layer, soil or litter is assumed to have a uniform heat conductivity. The model simplifies soil structure based on two soil layers plus a litter layer, if present. Inputs of energy to the ground surface and energy flow through the soil are schematized. Emphasis on inputs here ignores the potential role of evaporation from the soil. Soils in the Diamond Lake area are excessively drained and water puddling is rare (Radtke and Edwards 1976). Any moisture drawn up to the surface from deeper soil layers is considered negligible apart from plant transpiration.

REM 4.13.1. Discretization requires a cycling process to yield information about energy flow. Local array variables are established to hold values of coefficients in discretization equations and hold transitional values of soil depth, conductivity, and temperature.

Variables for temperatures of the surface boundary, the litter layer, A1 soil layer, and A2 soil layer have static variables between calls to SOILENERGY.

REM 4.13.2. The model assumes that chemical and physical characteristics of the A1 soil layer do not change during the 25-year planning period. By contrast, the depth of the organic litter above the mineral soil may change if changes occur in forest structure. Data on initial litter characteristics and soil characterization for organic matter, quartz (sand) fraction, porosity, and soil layer thickness come from primary characterization data for soil sample S91OR-019-002 at the National Soil Survey Center, Lincoln, NB. Calculations to determine soil and litter porosity follow methods and data from Hillel (1982). A soil damping temperature is estimated to be 5°C (Kimble 1993). Values for heat capacities for organic matter, quartz minerals, and air also come from Hillel (1982).

The soil sample modeled comes from Lemolo Lake, Douglas County, OR, at an elevation of 1187 m, about 500 m lower than stands being modeled near Diamond Lake and is characterized as a frigid typic [Andept]. Soil sample S82OR-019-002, a medial-skeletal dystric Cryand from extreme eastern Douglas County, OR, in the vicinity of the Diamond Lake pine mushroom management area would be more suited for modeling. The latter sample is not used here, however, because data on bulk density of the soil are not available.

REM 4.13.3. Initial annual values for variables are identical at the beginning of the snow-melt season, designated here as 21 March (day 80). All layer depths are given in centimeters. The soil and any organic litter layer are assumed to be saturated with water so that the fractions of water in both layers are equivalent to the porosities of those layers. The variable for boundary surface temperature, **T0!**, is set to the average daily temperature for day 80 every year. Initial temperatures for the A1 layer and combined lower layers are fixed at 0°C and 3°C respectively.

Some soil physical features change as the amount of water in the soil changes. First, whenever litter is present, the fraction of the volume of the litter layer that is water is determined from the amount of incoming soil water, either from snow melt or from rain. Refer to GASHCANOPY (section 4.4.7.) for rain and WEATHERDATA (section 4.3.16.) for snowmelt estimated to enter the soil. Water content and conductance of the A1 and A2 layer depend in part on the presence of an organic litter layer. The model assumes that inputs of water pass through to the top soil layer (A1) quickly and drain within 24 hours. The total amount of water reaching the ground occupies at most 79% of soil volume. For the soil modelled here, the maximum amount of effective rainfall held in the A1 layer is equal to the porosity percent times the distance from the midpoint of the upper layer to the next lower soil layer (that is, 0.79 x 8 cm). Runoff is omitted from the model as the pine mushroom harvest sites are flat or gently sloping. Below the A1 layer, other soil layers (lumped as a single A2 layer) are considered to have infinite capacity to drain water from the A1 layer in excess of pore space.

Litter and soil heat capacities are calculated sequentially by layer. Conductance values follow equations from Yin and Arp (1993, equations 8 through 10). Units for thermal conductance are J cm^{-1} s^{-1} $°C^{-1}$. The equations arranged by temperature and surface type are:

for both the organic litter layer and mineral soil layers above 0°C --

$$k_{>0°C} = \frac{5.57 * \theta^{0.8} + P}{10^{2.34*(P+0.5)}}$$

for organic litter layer below 0°C --

$$k_{\leq 0} = k_{\geq 0} * (3.5 + 4.3 * \theta * (6.3 + \theta) - 2.8P - 61.9 * \theta * P * (1.4 - P) \quad \text{and}$$

for mineral soil below 0°C --

$$k_{\leq 0°} = 0.00182 * (1 + 2.4.5 * \theta^2 + 16.5 * \theta * (\frac{32.4}{10.^{2.36*P}} + (\frac{100}{T+273}^{2.25}) - 1.09)), \quad \text{where}$$

k_T = thermal conductivity at temperature T°C;

P = porosity, that is the decimal fraction that is pore space in dried soils per unit of volume; and

θ = the decimal fraction per unit of soil volume that water occupies.

Thermal conductivity varies on a daily basis as a function of soil water content. Greater water content in the porous portions of soil improves thermal conductivity.

REM 4.13.4. The number of distinct layers of the forest floor and soil determines the number of iterations of the tridiagonal matrix algorithm. If a litter layer is present, the number of rounds is three, otherwise only the two soil layers are modelled.

The boundary layer heat capacity has a value of one and layer depth that approaches zero. Coefficients *a* through *d* describe the rates of change in soil temperatures as heat energy moves downward toward the damping layer depth. Once the values of *a* through *d* are determined for the lowest soil layer (A2 here), a back substitution begins based on the damping subsoil temperature. With each cycle of substitution, the next higher soil or litter layers receives a newly calculated temperature, culminating with the surface boundary layer temperature, **T0!**.

Note: The *d* term is valued as zero because the constant portion of the differential model is omitted in the discretization equation.

REM 4.13.5. The temperature for the A1 layer from the previous day is held by the variable **oldsoiltemp!**. New temperatures calculated for each layer in the discretization algorithm replace values from the previous day.

REM 4.13.6. Yin and Arp (1993) calculate a ratio of effective air to ground conductance (β_e) empirically. Their equation (21) uses solar radiation and leaf area index. This model substitutes leaf area index for vegetative area index and daily values of short wave energy to per day values based on daylength, as computed in WEATHERDATA. The equation is:

$\beta_e = 8.1 * \text{Solar} * (1 - e^{\min(\text{siteLAI},\ \text{maxLAI}) - 6.})$, where

Solar = daily solar radiation;

siteLAI = leaf area index as measured in LEAVES (section 4.3.9.); and

maxLAI = the functional maximum leaf area index to attentuate solar energy.

The beta value is extrapolated here for the purposes of calculating a new boundary layer temperature.

REM 4.13.7. The surface boundary conductance is calculated from Yin and Arp (1993, equation 3):

$$T_0 = \frac{T_v}{(1+\beta_e)} + \frac{\beta_e}{1+\beta_e} * (Tfactor + \frac{NetEnergy}{k_1/(x_1/2)})$$

where T_0 = boundary temperature;

T_v = air temperature just above the ground;

k_1 = thermal conductivity;

NetEnergy = net energy flux - the sum of both short- and longwave energy; and

Tfactor = temperature at the middle of the top layer (litter layer or soil mineral layer, depending on the presence or absence of a litter layer).

In instances where there is no organic litter layer the variable **tfactor!** takes the value of the mid-layer temperature of the A1 layer. When an organic layer is present, the mid-layer temperature from the organic layer is the **tfactor!**.

New values for the A1 soil temperature and for the change in soil temperature in the A1 layer from the previous day are returned to WEATHERDATA so that that subprogram registers the amounts of change in soil moisture and temperature in the upper soil layer where pine mushroom mycelia and mycorrhizae concentrate. WEATHERDATA also forwards information from SOILENERGY about the amount of water absorbed by the soil to MUSHROOMYIELD (section 4.3. 10.) to predict the number of flushes during the autumn mushroom season in production scenario twelve.

4.4.14. TREEHEIGHT

Function - Establish the ages of trees in the stand at year zero

Furnish estimates of maximum annual increments for tree height growth in subsequent years

Variables Imported: age%, record%, siteindex!, species%

Variables Exported: potentialheight!

TREEHEIGHT estimates the ages of trees at the beginning of each simulation when AGES (section 4.3.1.) calls the subprogram. In subsequent years, TREEHEIGHT estimates the maximum potential height growth for trees in BIGHEIGHTGROW (section 4.4.2). Equations for the individual species are presented in table 4.4.

REM 4.14.1. Species-specific equations used in this model are the same as those used in the subroutine HTCALC in the West Cascades variant of the FVS (Donnelly 1995), with one exception noted below.

REM 4.14.2. The height equation for Pacific silver fir comes from Hoyer and Herman (1989, equation 4). It is based on a 100-year site index. Tree age is measured at dbh; therefore, the equation adds 4.5 ft to the potential height. Tree data were collected from Stevens Pass, Washington, to MacKenzie Pass, Oregon.

REM 4.14.3. The height equation for lodgepole pine comes from Dahms (1964, p. 7 - footnote 1). It is based on a 50-year site index. Tree height is estimated from tree age at the ground. Data are from central and south-central Oregon.

REM 4.14.4. The height equation for western white pine comes from Curtis and others (1990, equation 3). It is based on a 100-year site index. Tree age is measured at dbh;

therefore, the equation adds 4.5 feet to the potential height estimated by the equation. Data are from the Mount Hood and the Gifford Pinchot National Forests.

REM 4.14.5. The height equation for red fir is from Dolph (1991, equation 3) and serves both Shasta red fir and California red fir. It is a 50-year site index. Age is measured at dbh; therefore, the equation adds 4.5 ft to the potential height estimated by the equation. The complex equation is divided into components here to facilitate users' grasp of the equation. Data were collected from southwest Oregon to the southern Sierra Nevada in California.

REM 4.14.6. The height equation for mountain hemlock comes from Means and others (1986 ms., equation 9) and is different from the equation used in the West Cascades variant of the FVS (equation 10). The equation chosen is the form to predict height for mountain hemlock in plant association types with sparse forest understories consisting primarily of *Chimaphila* spp. and *Vaccinium scoparium*, typical of the pumice and ash deposition zones in the Cascade Range. The equation used in FVS tends to underestimate tree growth on low productivity sites (Means and others 1986 ms.).

The equation computes mountain hemlock height from a metric site index. Height is then converted to English feet to conform with the English measurements used to model tree growth in the West Cascade variant of the FVS. Sampled trees ranged from the Gifford Pinchot National Forest south to the Oregon-California border.

Table 4.4. Site index equations used for the tree species modeled in MUSHROOM.

Pacific silver fir:

$$\text{PotentialHeight} = 4.5 + \text{SiteIndex} * (1.0 - \exp(-(0.0071839 + 0.0000571 * \text{SiteIndex}) * \text{Age})^{1.39005} / (1.0 - \exp(-(0.0071839 + 0.0000571 * \text{SiteIndex}) * 100)^{1.39005}$$

lodgepole pine:

$$\text{PotentialHeight} = \text{SiteIndex}_{100} * (-0.0968 + 0.02679 * \text{Age} - 0.00009309 * \text{Age}^2)$$

western white pine

$$\text{PotentialHeight} = 4.5 + (\text{SiteIndex}_{100} - 4.5) * (1.0 - \exp(-\exp(-4.625365 + 1.346399 * \ln(\text{Age}) - 135.354483/\text{SiteIndex}_{100}))) / (1.0 - \exp(-\exp(-4.625365 + 1.346399 * \ln(100) - 135.354483/\text{SiteIndex}_{100})))$$

red fir

$$\text{PotentialHeight} = 4.5 + ((\text{SiteIndex}_{50} - 4.5) * (1.0 - \exp(-B * \text{Age}^{1.51744}))) / (1.0 - \exp(-B50 * 50^{1.51744})),$$ where

$$B = \text{Age} * \exp(\text{Age} * (-4.40853 * 10^{-2})) * 1.41512 * 10^{-6}) * \text{SiteIndex} + (\text{Age} * \exp(\text{Age} * -4.40853 * 10^{-2}) * 1.41512 * 10^{-6})^2 * (-3.04951 * 10^{6}) + 5.72474 * 10^{-4}$$, and

$$B_{50} = 50 * \exp(50 * (-4.40853 * 10^{-2})) * (1.41512 * 10^{-6}) * \text{SiteIndex}_{50} + (50 * \exp(50 * (-4.40853 * 10^{-2})) * 1.41512 * 10^{-6})^2 * (-3.04951 * 10^{6} + 5.72474 * 10^{-4})$$

mountain hemlock

$$\text{PotentialHeight} = ((14.5791 + 1.365410 * \text{SiteIndex}_{100}) * (1.0 - \exp(-0.00321964 * \ln(\text{SiteIndex}_{100}) * \text{Age}))^{1.4887813 + 1.1031438/\text{SiteIndex}_{100}})$$

4.4.15. WOODDEFECT

Function - Estimate the amount of stem defect in a tree bole based on the tree age

Variables Imported: age%, record%, species%

Variables Exported: defect!

REM 4.15.1. Harmon and others (1996) developed equations to calculate percentage of defect in live trees. Equations with three decay coefficients for live trees take the form:

DefectPercent = DecayCoeffA / (1 + DecayCoeffB + exp(-DecayCoeffC * TreeAge)

where TreeAge is the age at breast height. Coefficients for western hemlock were used for mountain hemlock, and coefficients for white fir were used for Shasta red fir.

Both DEATH (section 4.3.7.) and VOLUMECALC (section 4.3.15.) call WOODDEFFECT for dead trees and for live trees, respectively.

4.4.16. WOODPRICES

Function - Furnish prices for wood products and their manufacturing costs

Variables Imported: betamultiplier!, calendaryear%, normal!, species%, woodpricescenario!

Variables Exported: alpha!, beta!, conversioncost!, functionnumber%, hemfirmanufacturingcost!, pinemanufacturingcost! **plus** lumber and chip prices by tree species and lumber grade

REM 4.16.1. The model presents two scenarios to describe future prices and production costs for wood products. Products considered here are lumber, wood chips, and sawdust. The user specifies in the core program which scenario to apply.

REM 4.16.2. The first scenario uses product prices based on the historical record of lumber grade prices published by the Western Wood Products Association (WWPA) for the period 1971-1995. Composite lumber grade categories are based on the system of classification used in Haynes and Fight (1992) for hem-fir species. Susan Willits at the Portland, OR, Laboratory of the Pacific Northwest Research Station has developed the composite lumber grades for lodgepole pine and western white pine used here. Prices for lumber in respective composite grades are based on the weighted averages the prices of all component grades as recorded in WWPA annual summaries (see Weigand 1997a for component grades). All nominal prices have been converted to inflation-adjusted prices expressed in 1990 U.S. dollars using the producer price index for manufactured goods (Office of the President 1996).

The 1995 chip value is the estimated price for 1995 from the Timber Assessment Market Model (Adams and Haynes 1996). All chip prices used here are prices per bone dry short tons (2,000 lbs.).

Costs of manufacturing, administration, post-harvest land restoration, and transport are derived from appraised costs for U.S. Forest Service timber sales at the Diamond Lake Ranger District, for the period 1971-1991. Values from 1991 were used in 1995, values from 1990 were used in 1996 projections, values from 1989 were used in 1997 projections, etc. The same methods were used with lumber grade prices. This reversed chronological order assumes that real prices of wood products and their associated costs do not increase over time. Instead, prices are cyclical, with the most recent price cycle cresting in 1993. Therefore, prices from two years before the crest are assumed to forecast prices two years after the crest (the pair 1991/1995 in this example). Comparable years in the cycle of rising and falling real lumber prices are presented in table 4.5.

In this scenario a fifteen- or sixteen-year cycle between peaks is projected. Therefore, another peak is forecast to occur in 2008. Past years have their values assigned a pair of future years on either side of the price peak.

REM 4.16.3. The second scenario provides prices derived from the Timber Market Assessment Model (TAMM), used by the U.S.D.A. Forest Service to project national timber markets in reports to Congress (Adams and Haynes 1996). Projected prices for aggregate lumber from the Pacific Northwest from the TAMM provide pegs against which prices for individual lumber grades being modeled are derived. The price relations from 1971 to 1995 for the species-specific lumber grades regressed against the regionwide average lumber prices form the historical basis. This scenario assumes the the historical relations among prices for lumber grades continue but that timber prices as modelled in the TAMM are trending upward in the future. Regression equations are based on Weigand (1997a). See tables 4.6. and 4.7., respectively, for TAMM baseline prices for lumber for the Pacific Northwest and for the historical price relations between species-specific lumber grades and average regional lumber prices.

Chip prices from Diamond Lake timber sales were found to have a uniform distribution ranging from $24 to $83 in constant 1990 U.S. dollars. Pine chip prices maintain a constant ratio of 0.91 to hem-fir chip prices. Stochastic pricing of inflation-adjusted production costs is in most cases a function of the historic probability distributions of costs. Real costs are assumed to be independent of one another and, except for stump-to-truck costs, do not show time trends. The following distributions of timber sale costs were derived from Diamond Lake timber sales for use in the second wood price scenario:

administration costs	norm (22.4, 3.76)
restoration costs	unif (15,36)
transport costs	beta (33,31).

Stump-to-truck costs follow the regression:

$$\text{Cost} = \exp(-30.651 + 0.17437 * \text{calendar year}).$$

Table 4.5. Pairings of years under the assumption of cyclical real lumber prices in the Pacific Northwest.

Source year for prices	*Equivalent forecast for future years*
1978	2008
1979	2007, 2009
1980	2006, 2010
1981	2005, 2011
1982	2004, 2012
1983	2003, 2013
1984	2002, 2014
1985	2001, 2015
1986	2000, 2016
1987	1999, 2017
1988	1998, 2018
1989	1997, 2019
1990	1996, 2020
1991	1995

Table 4.6. Projections of average lumber prices in the U.S. Pacific Northwest from the Timber Assessment Market Model (TAMM - 1993 version, run LR 207), 1996-2020.

Year	Westside	Eastside
	-- *1990 U.S. dollars*--	
1996	380.54	446.80
1997	384.58	451.56
1998	369.84	436.43
1999	371.52	437.42
2000	366.92	434.06
2001	370.93	431.37
2002	376.67	428.68
2003	378.24	430.35
2004	387.42	439.53
2005	392.30	444.41
2006	392.49	444.50
2007	387.78	439.99
2008	392.92	444.85
2009	394.57	446.88
2010	398.87	451.25
2011	408.75	460.76
2012	416.76	469.87
2013	427.68	480.03
2014	435.42	488.42
2015	432.65	485.09
2016	430.46	482.20
2017	433.09	485.46
2018	434.57	487.29
2019	437.34	489.19
2020	434.83	486.05

Source: Adams and Haynes 1996

Table 4.7. Regression coefficients for lumber prices of selected species groups and lumber grades from western United States mills.

species group and grade	b_0	b_1	adjusted r^2	Durbin-Watson statistic	equation form	base price source
hem-fir						
D select and shop	148.01*	1.0859***	0.82	2.1384‡	1	west-side
structural items	0.3322 ($p(b_0=0)=.40$)	0.9527***	0.97	1.2418‡	2	west-side
heavy framing	19.479 ($p(b_0=0)=.21$)	1.0167***	0.95	1.2483	1	west-side
light framing	1.4211 ($p(b_0=0)=.94$)	0.8726***	0.96	1.5717‡	1	west-side
utility	-0.9025*	1.0655***	0.87	1.3456	2	west-side
economy	0.1521 ($p(b_0=0)=.91$)	0.7915***	0.70	2.1796‡	2	west-side
western white pine						
D select and better	3.1732*	0.6512**	0.45	2.0540‡	2	east-side
2 common	342.51***	0.7394***	0.40	1.5358‡	1	east-side
3 common	0.0157 ($p(b_0=0)=.98$)	0.9883***	0.80	1.9225	2	east-side

Table 4.7. continued.

western white pine continued						
4 common	-1.1727***	1.1417***	0.93	1.9754	2	west-side
5 common	-4.6944***	1.5798***	0.84	1.6651	2	east-side
lodgepole pine and other whitewoods						
2 common	2.6568***	0.6045***	0.72	1.8185	2	west-side
3 common	67.650 ($p(b_0=0)=.11$)	0.6363***	0.79	1.8048‡	1	west-side
4 common	-0.1741 ($p(b_0=0)=.89$)	0.9375***	0.77	2.3395	2	east-side
utility	80.357 ($p(b_0=0)=.18$)	0.4731***	0.77	1.6815‡	1	west-side
5 common	-0.8731 ($p(b_0=0)=.26$)	0.9352***	0.72	1.3155	2	east-side

Source: Weigand (1997a)
n=25 except for lodgepine pine and where noted, n=22 for lodgepole pine
* significant at p<=.10
** significant at p<=.05
*** significant at p<=.01,
‡adjusted for serial autocorrelation

REM 4.16.4. The cost of converting timber to lumber consists of four elements: the cost of sale administration for ranger district staff, the cost of site restoration including planting trees, stump-to-truck costs, and transport costs to a lumber mill. All conversion costs are figured per one thousand Scribner board feet, log scale.

4.4.17. WOODUSE

Function - Calculate the stumpage prices for individual trees

Variables Imported: conversioncost!, cvts!, dbh!, hemfirmanufacturingcost!, hgt!, merchvolume!, pinemanufacturingcost!, prune%, prunedportion!, record%, species%, record%, scribner6! **plus** lumber and chip prices by tree species and lumber grade

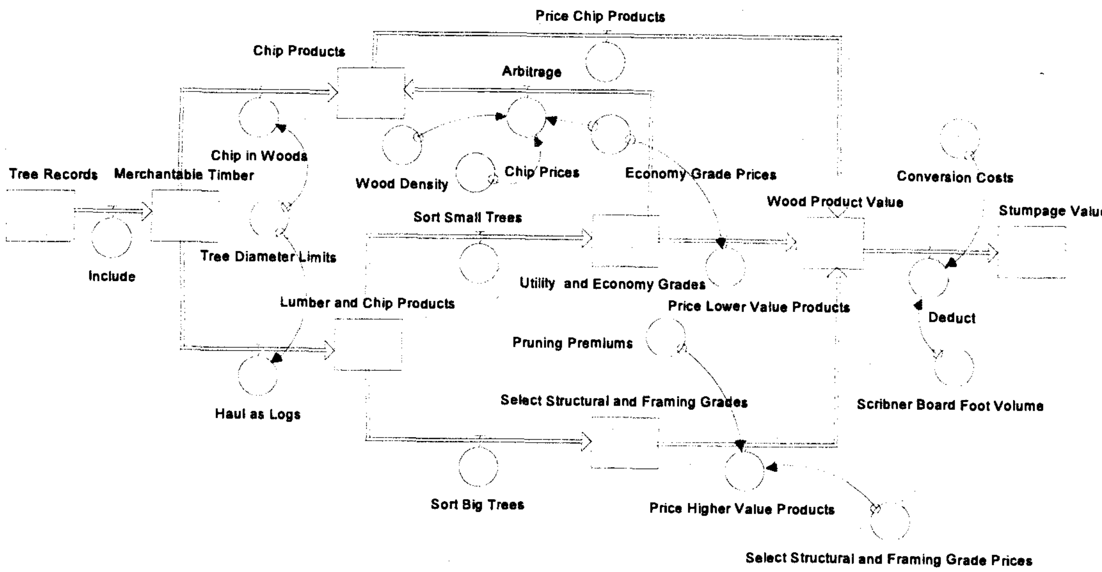
Variables Passed: logheightnow!, unbiaseddbh!

Variables Exported: valuewoodproducts!

REM 4.17.1. WOODUSE receives tree records one at time from STUMPAGEPRICING (section 4.3.13.). Constant values for converting Scribner board feet to cubic feet and the lumber recovery rates pruned trees from lumber milling are set here in advance of use. The initial setting for the binary variable **bigtree%** is set at "no." Species-specific wood densities expressed in pounds dry weight for per cubic volume of green lumber come from Hartman and others (1976). The density value used for lodgepole pine is taken from the value for ponderosa pine, the value used for mountain hemlock is extrapolated from western hemlock, and Shasta red fir uses the same value as for Pacific silver fir.

The Timber Quality Research Project at the Portland, OR, Laboratory of the Pacific Northwest Research Station has conducted mill utilization studies for commercial species. The studies provide databases to create regression equations that predict lumber

Figure 4.19. A schematic overview of WOODUSE.



production. Regressions and data sets of these unpublished studies are on file at the Laboratory. Trees with dbh's greater than or equal to the lower limit of tree dbh's used in the species-specific mill studies switch the variable **bigtree%** to "yes." For example, the hem-fir mill study of timber from the Central Oregon Cascades included Pacific silver fir trees with dbh's twelve inches and larger.

Trees larger than the minimum merchantable dbh but smaller than the lower diameter limit for mill studies of their species are modelled as though they were milled as lodgepole pine. Lodgepole pine is the species with the lowest diameter limit at seven inches - the minimum merchantable dbh for lumber. Lodgepole pines are never classified as big trees.

REM 4.17.2. WOODUSE classifies a tree record by dbh class and species. Three dbh classes are recognized:

- trees with dbh's greater than or equal to the minimum merchantable dbh size for lumber production;
- trees with dbh's greater than the lower limit for "in-woods chipping" but less than the minimum merchantable dbh size for lumber; and
- tress with dbh's less than the chip limit, which may be thinned but have no wood-product value.

REM 4.17.3. Lumber value for a tree bole is the sum of the values of lumber produced in each composite lumber grade from a tree bole. The regressions predict volume production of lumber according to a composite lumber grade. Composite lumber grades have been developed at the Portland Forestry Sciences Laboratory to summarize price trends among similar or substitutable tree grades reported in monthly summaries by the Western Wood Products Association, Portland, OR (Anonymous, 1971-1995). Composite grades for hem-fir lumber follow the system devised by Haynes and Fight (1992). Susan Willits has developed the composite lumber grades for sugar pine (substituting here for western white pine) and lodgepole pine used here. Weigand (1997a) provides a complete list of lumber grades reported by the Western Wood Products Association from 1971 through 1995 grouped by composite grade.

Regression equations for each composite lumber grade used in WOODUSE are presented in table 4.8. The regression equations for lumber production first calculate the net Scribner volume in board feet of lumber. Other equations give the volume in tons for bone-dry chips and sawdust produced from the same tree. Table 4.9. summarizes the chip and sawdust equations. Dependent variables are the dbh and height of one tree represented by a record. Dividing net Scribner volume by 1,000 gives the thousand board foot (mbf) volume. Prices for lumber are conventionally expressed on an mbf basis. The mbf volume for the lumber grade is then multiplied by the current year price per mbf of

Table 4.8. Equations to predict board foot volume of rough green lumber produced from harvested trees.

Species and Lumber Grade	*Equation*		*Statistical Significance*
Pacific silver fir / noble fir			
select	$bdft = -168.754269 + 0.005110*dbh^2$	adj. $r^2 = 0.81$	intercept dbh^2 significant at $p < 0.0001$
structural	$bdft = -228.649317 + 5.652505 * dbh - 0.000927 * dbh^2 + 2.113128 * height$	adj. $r^2 = 0.44$	coefficient for dbh significant at $p < 0.05$; intercept and coefficients for other variables significant at $p < 0.001$
heavy framing	$bdft = -833.769849 + 31.181626 * dbh - 0.002721 * dbh^2 + 6.461609 * height$	adj. $r^2 = 0.59$	coefficient for dbh^2 significant at $p < 0.05$; intercept and coefficients for other variables significant at $p < 0.001$
light framing	$bdft = -324.054012 + 25.004350 * dbh$	adj. $r^2 = 0.71$	intercept and coefficients for both variables significant at $p < 0.0001$
utility	$bdft = -166.926016 + 5.261027 * dbh + 1.185643 * height$	adj. $r^2 = 0.56$	coefficient for height significant at $p < 0.01$; intercept and coefficient significant at $p < 0.001$
economy	$bdft = -22.740824 + 0.000874 * dbh^2$	adj. $r^2 = 0.53$	intercept significant at $p < 0.05$ coefficient for dbh^2 significant at $p < 0.0001$

Table 4.8. Continued.

western hemlock / grand fir / white fir (surrogates for Shasta red fir and mountain hemlock)

select	bdft = 809.327668 - 33.872746 * dbh + 0.011199 * dbh^2 - 5.743564 * height	adj. r^2= 0.87	intercept and all coefficients significant at $p < 0.0001$
structural	bdft = - 484.339101 + 23.582593 * dbh - 0.002197 * dbh^2 + 3.278993 * dbh	adj. r^2= 0.29	intercept significant at $p < 0.0001$ coefficients significant at $p < 0.001$
heavy framing	bdft = -799.575748 + 22.325154 * dbh - 0.001553 * dbh^2 + 5.66057 * height	adj. r^2= 0.63	dbh^2 coefficient significant at $p < 0.01$; intercept and other coefficients significant at $p < 0.0001$
light framing	bdft = -235.028019 + 0.001721 * dbh^2 + 3.287810 * height	adj. r^2= 0.80	intercept significant at $p < 0.001$; coefficients significant at $p < 0.0001$
utility	bdft = 37.918634 + 6.28234 * dbh + 0.000505 * dbh^2 - 1.113004 * height	adj. r^2= 0.52	intercept not signicant at $p < 0.05$; dbh and dbh^2 coefficients significant at $p < 0.05$; height coefficient significant at $p < 0.01$
economy	bdft = 76.530349 + 0.002083 * dbh^2 -1.196416 * height	adj. r^2= 0.69	intercept not significant at $p < 0.05$; height significant at $p < 0.05$; dbh^2 significant at $p < 0.0001$

Table 4.8. Continued.

sugar pine (surrogate for western white pine)			
select	bdft = -80.950728 + 0.001689 * dbh^2	adj. $r^2 = 0.71$	intercept and coefficient significant at $p < 0.001$
2 common	bdft = -126.255362 + 0.007566 * dbh^2	adj. $r^2 = 0.95$	intercept and coefficient significant at $p < 0.001$
3 common	bdft = -185.860597 + 14.902847 * dbh^2	adj. $r^2 = 0.45$	intercept and coefficient significant at $p < 0.001$
4 common	bdft = 10.914323 + 0.000222 * dbh^2	adj. $r^2 = 0.43$	intercept significant at $p < 0.05$; coefficient significant at $p < 0.001$
5 common	bdft = 2.212092 + 0.000103 * dbh^2	adj. $r^2 = 0.34$	intercept not significant at $p < 0.50$; coefficient significant at $p < 0.001$
lodgepole pine			
3 common	bdft = -27.945545 + 0.015114 * dbh^2	adj. $r^2 = 0.89$	intercept and coefficient significant at $p < 0.0001$
4 common / utility	bdft = 1.119905 + 0.000517 * dbh^2	adj. $r^2 = 0.08$	dbh^2 coefficient significant at $p < 0.001$; intercept not significant at $p < 0.05$
5 common	bdft = -2.122541 + 0.000857 * dbh^2	adj. $r^2 = 0.39$	intercept significant at $p < 0.05$; dbh^2 coefficient significant at $p < 0.0001$

Table 4.9. Chip and sawdust recovery equations for timber species found at the Diamond Lake pine mushroom management area.

Species and Wood Product		*Equation*
Pacific silver fir / noble fir		
>= 12 in dbh		
	chips	= (35.857788 + 0.000045527 * dbh^2 - 0.159824 * height) * merchantable volume
	sawdust	= (7.79201 - 0.000003649 * dbh^2 + 0.159824 * height) * merchantable volume
western hemlock / grand fir / white fir (surrogate for Shasta red fir and mountain hemlock)		
> = 10 in dbh		
	chips	= (31.295377 - 0.078295 * dbh^2) * merchantable volume
	sawdust	= (8.21878 + 0.005459 * height) * merchantable volume
sugar pine (surrogate for western white pine)		
> = 12 in dbh		
	chips	= (83.807384 - 2.578532 * dbh + 0.02618 * dbh^2) * merchantable volume
	sawdust	= (5.213312 + 0.234969 * dbh + 0.003012 * dbh^2) * merchantable volume
lodgepole pine		
all dbh's for lodgepole pine		
all dbh's less than minimum dbh limits for other tree species		
	chips	= (73.459231 - 2.403497 * dbh) * merchantable volume
	sawdust	= (4.748349 + 0.413004 * dbh) * merchantable volume

Note: Product recovery is expressed as a percent of total volume.

that lumber grade to give the value of a single grade of lumber produced from a single tree. Prices in the model are determined from one of two wood price scenarios in WOODPRICES (section 4.4.16.). These values are passed to WOODUSE by way of STUMPAGEPRICING.

Regressions for hem-fir and lodgepole pine lumber types are used for more than one species. Hem-fir equations apply to Pacific silver fir, Shasta red fir, and mountain hemlock; lodgepole pine equations are applied to all species with dbh's smaller than the diameter range covered by specific mill studies. Species-specific data from mill studies are lacking for Shasta red fir and mountain hemlock. Data from a combined mill study of western hemlock, grand fir (*Abies grandis* Dougl. ex D. Don) Lindl., and white fir are used to represent these two species.

Note: Equations for chip and sawdust volumes include division by 100 to convert percentages of volumes of chips and sawdust to decimal fractions.

REM 4.17.4. In some years, the price of chips is high enough that the value of chips produced from the same volume of economy grade lumber or 5 common grade lumber is greater than the value of lumber produced. In other years, the value of economy and 5 common grades is high enough that lumber rather than chips are produced. The flexibility to produce either chips or low-grade lumber is an instance of price arbitrage. People decide whether to
process the tree bole volume as lumber or as chips depending on product prices. The computer code with the variables **valueeconomy!**, **value5common!**, and **valueeconomyweight!** reproduces the decision process in arbitrage.

To decide whether to produce chips or lumber, the volume in thousand board feet for economy or 5 common lumber must be converted first to a cubic foot volume with the reciprocal of the board foot to cubic foot conversion rate, **bdft2cuft!**. Then the species-specific wood density in units of pounds per cubic feet is multiplied by the cubic foot volume estimate to arrive at a pound weight. The pound weight is converted to English tons and multiplied by the yearly average price for the appropriate type of chips (hem-fir or pine) to get the value of the wood volume as chips.

Note: The board foot volumes calculated here are net board foot lumber volumes not gross log board foot volumes. Gross board foot volumes are computed in WOODVOLUMES (section 4.4.18.) to determine production costs of converting logs to lumber.

REM 4.17.5. For lack of adequate data on western white pine logged as live trees, mill study data for sugar pine serve as a surrogate to predict timber conversion to lumber.

REM 4.17.6. Data for wood product recovery are not available for small-diameter merchantable trees, except for lodgepole pine. When trees of species other than lodgepole pine, with smaller dbh's are milled, all utilization is identical with that of lodgepole pines with two exceptions:

- chip value is priced using hem-fir prices rather than as pine chip prices for boles of hem-fir species; and
- value added from any pruning premiums is figured for hem-fir species rather than as for pines, if the species of the tree record is a hem-fir species.

REM 4.17.7. When trees have been previously pruned to the height of the first tree log, 17.5 feet, the subprogram checks the value for **prune%** belonging to the tree record. If the value of the variable equals three. WOODUSE then calls PRUNINGPREMIUM (section 4.4.9.) to estimate the markup in value resulting from improved wood quality with the increased production of clear (that is, knot-free) woods from pruned trees.

Pruning trees increases the volume of lumber produced from a tree and correspondingly reduces chipped volume. The increase in lumber recovery is an improvement in product quantity. Shifts to production of more valuable lumber grades may occur as well. These are improvements in product quality. Both improvements bring increased value to logs from pruned trees.

Only shifts to increased timber volume are modeled for pruned logs of hem-fir species. Proportional increases in lumber volume are modeled identically for all hem-fir species at all dbh's based on data provided by Cahill (1991) for ponderosa pine recovery. Lumber increases its share of butt log volume by 8.8 percent while chip volume declines by the identical volume in the butt log. The added lumber volume is modeled as though it were priced at the average price of lumber produced from an unpruned log of the same dimensions. Markup for timber from the hem-fir species is modelled here in three steps:

- calculate the ratio of volume encompassed by the pruned butt log to the entire merchantable tree volume;
- calculate the theoretical net increase in value resulting as lower-priced chip volume is converted added higher-value lumber volume; and
- calculate the markup as the product of the proportion of pruned volume in a tree, the added recovery, the lumber volume obtained without pruning, and the difference in unit prices between lumber and chips.

The equation used is:

$$\text{Markup} = \text{PrunedVol\%} * (\text{Recovery} - 1) * (\text{LumberVolume}) * (\text{LumberValue} - (\text{ChipPricePerTon} * \text{LumberVolume} * \text{Convert} * \text{WoodDensity}/2000))$$

where Markup = the extra value added from pruning the butt log;

PrunedVol% = the percentage of total tree wood volume in the butt log;

Recovery = the proportional increase in lumber yield from a pruned butt log;

LumberVolume = the volume in board feet of lumber from a whole

	unpruned tree with the same dimensions as the pruned tree;
LumberValue	= the lumber value from the same unpruned tree;
ChipPricePerTon	= the value of chips produced from the same unpruned tree based on a price expressed in English tons;
Convert	= the conversion factor from board feet to cubic feet; and
WoodDensity	= wood density in units of dry weight in pounds divided by cubic volume.

The equation is made awkward by the fact that the unit lumber value is measured in thousand board feet and the unit chip value is measured in bone-dry tons.

Premiums for pine species include a shift in the proportions of lumber to more valuable grades as well. For lodgepole pine, the quality shift premium is modeled as an index of changing prices relationships between 3 common and 4 common lumber:

$$AdjustedPrice = (3CommonPriceNow/3CommonPrice1988)/(4CommonPriceNow/4CommonPrice1988)$$

The adjustment accounts for possible changes in the ratios between current year prices and prices in 1988 during Cahill's study. All prices are expressed in constant 1990 U.S. dollars. With western white pine, the adjustment takes the same equation form, but the lumber grade composition is assumed to shift from 2 common grade to select grade lumber.

Cahill's data for trees with 75 percent clear butt log volume from pruning are taken as an average across the range of butt logs with small-end diameters between ten and twelve inches. An approximate regression derived from that data predicts premiums at real 1988 prices for 75% pruned butt logs in contrast to unpruned butt logs. The regression is:

$$QualityPremium1988 = -216.41 + 138.20 * \ln(TopEndLogDiameter).$$

The pruning markup in total value for wood from an entire tree is formulated as follows:

$$Markup = Vol\%Pruned * (QualityPremium * AdjustPrice * LumberPremium - ChipValueLoss).$$

The markup is then added to the other product value components to give the total value of wood products from a tree.

REM 4.17.8. The value of products from a single tree large enough to produce lumber is the sum of the values from each composite timber grade, chip and sawdust values, and any markup for timber quality. Net value is obtained by deducting conversion costs (see WOODPRICES, section 4.4.16.) and species- specific manufacturing costs from the gross merchantable value.

REM 4.17.9. Trees below the merchantable dbh for lumber production but with dbh's greater than or equal to four inches are harvested for chips. The chip volume for these trees is calculated from their cubic volumes and their species-specific wood density.

Note: Trees with dbh's less than four inches, such as are found in "pre-commercial" thinnings may have economic value as hogged fuel or firewood. Demand for these products is sporadic. Good information about hogged fuels use and pricing is not available. In the model, small unmerchantable trees are tallied as part the annual deposition of organic matter in the stand. Small tree wood may be left on the ground to decompose or may be piled and burned (see CULTURE, section 4.3.6.).

At the conclusion of one call to the subprogram, the value of the lumber, chips, and sawdust produced by one tree represented by the current live or dead tree record is returned to STUMPAGEPRICING (section 4.3.13).

4.4.18. WOODVOLUMES

Function - Calculate measures of wood volume for individual trees.

Variables Imported: dbh!, hgt!, record%, species%

Variables Exported: cvts!, merchvolume!, scribner6!

WOODVOLUMES produces three measures to calculate wood volumes:

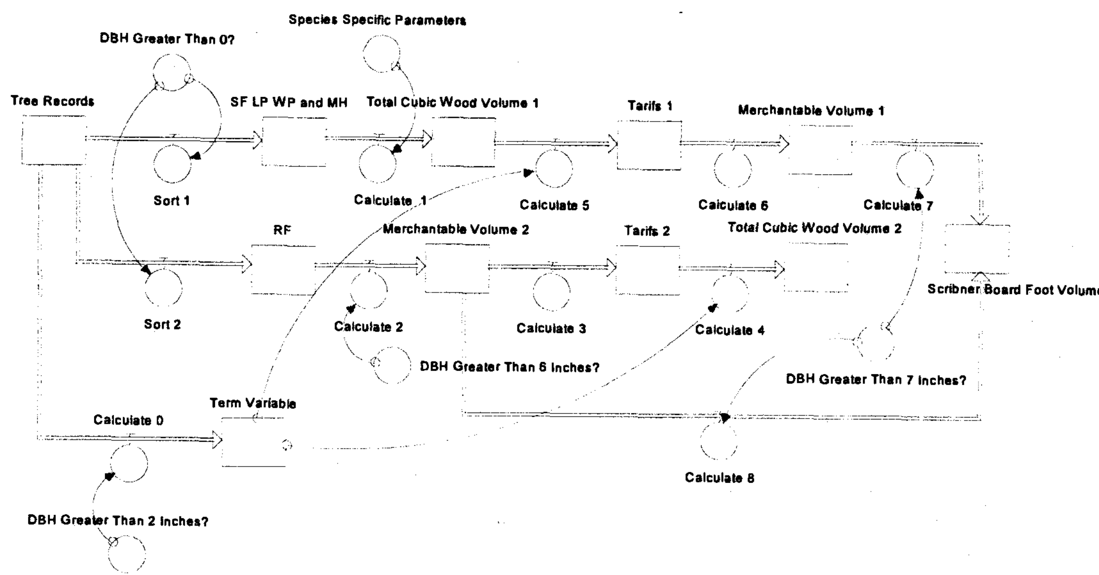
- total cubic foot tree volume from the ground to treetop;
- cubic foot volume from a one-foot high stump to the bole height having a four-inch diameter inside bark; and
- Scribner board foot volume for sixteen-foot logs bucked from stumpheight to the bole height having a six-inch diameter inside bark.

The system used here to calculate wood volumes is the same as that used by the Forest Inventory and Analysis Unit of the U.S.D.A. Forest Service, Pacific Northwest Research Station in their inventories of Pacific Coast states.

REM 4.18.1. VOLUMECALC (section 4.3.15.) exports data on tree basal area, diameter, height, and species to WOODVOLUMES. These data may be from any live or dead trees taller than breast height. Calculations of wood volumes are the same for both live and dead trees. Subsequently, VOLUMECALC calculates volume deductions for wood decay and defect.

Trees shorter than breast height have zero values for all three volume calculations. Trees with dbh's greater than or equal to one inch are considered in volume calculations, and trees with dbh's less than two inches are assigned a different equation to calculate total wood volume than the equation used for larger trees. The variable **term!** is an adjustment factor for calculating other measures of cubic volume from one that is already known (Brackett 1977).

Figure 4.20. A schematic overview of WOODVOLUME.



REM 4.18.2. Volume units are expressed in cubic feet and board feet, Scribner scale. Equations for whole tree cubic volumes take the form:

$$CubicVolume_{total} = 10^{a} * DBH^{b} * Height^{c},$$

where dbh is in inches and height is in feet. Coefficients for Pacific silver fir and lodgepole pine trees are taken from British Columbia sources in Brackett (1977). Volumes of western white pine trees are measured with the same exponential parameters used for lodgepole pine. Coefficients are presented in Table 4.10.

The system of volume calculation is based on tarifs. A tarif number is the cubic-foot volume of a tree having a basal area of one square foot at breast height from a one-foot high stump to the bole height having a four-inch diameter inside bark. The tarif value is the basis for calculating volumes of other trees of the same species with different basal areas. Chambers and Foltz (1981) summarize the tarif system for calculating tree volumes.

Table 4.10. Equation coefficients for measuring cubic volumes of trees using the British Columbia tarif system.

Tree Species	*Coefficients* a	b	c	*Source*
Pacific silver fir	-2.575642	1.806775	1.094665	Brackett (1977)
pine species	-2.615591	1.847504	1.085772	Brackett (1977)
mountain hemlock	-2.9561	1.8140597	1.2744923	Bell and (1981) others

Conventionally, the total cubic volume, **cvts!**, is estimated from species-specific coefficients and the tarif for the species allows for computation of the merchantable cubic volume to a tree bole height having either a four-inch or six-inch diameter inside bark. All species except Shasta red fir are calculated in this way here.

REM 4.18.3. Volumes of Shasta red fir trees are calculated in reverse order. Calculations for Shasta red fir begin with regression equations developed by MacLean and Berger (1976) for merchantable wood volume from a one-foot stump height to a bole height having a four-inch diameter inside bark. A cubic form factor, **cuftfactor!**, adjusts for taper using the equation form:

$$\text{CubicFormFactor} = 0.231237 + 0.028176 * \text{TreeHeight}/\text{DBH}.$$

Multiplying the cubic form factor by tree basal area, **rfba!**, expressed in square feet, and tree height produces the merchantable cubic volume, which is converted to the tarif value using an adjusted basal area value. For large trees, multiplying the resulting **tarif!** and **term!** and dividing by basal area adjustment gives the total bole volume (**cvts!**).

The original data used by MacLean and Berger (1976) did not include small trees. Merchantable cubic volumes of Shasta red fir trees with dbh's between five and six inches are extrapolated from MacLean and Berger equations by computing the cubic foot form factor as for a tree with a six-inch diameter tree with an additional tarif adjustment developed by mensurationists at the Pacific Northwest Research Station (Waddell 1997). The product of the **tarif!** and the **term!** variables gives the total bole value of smaller Shasta red fir trees.

Trees of all species with dbh's less than five inches are considered to have no merchantable cubic volume.

REM 4.18.4. Bell and others (1981) provide coefficients for mountain hemlock comparable to those for Pacific silver fir and lodgepole pine. Data on which coefficients are based were collected in the central Oregon Cascade Range.

REM 4.18.5. All trees, except Shasta red fir, with dbh's greater than five inches, have tarifs derived from their total cubic volumes. The tarif with tree basal area produces an estimate of the merchantable cubic volume from a standard equation for merchantable volume. Smaller trees have zero merchantable cubic volume but contribute to total cubic wood volume for the stand.

REM 4.18.6. Board foot volumes are calculated here as well using the Scribner sixteen-foot log rules for trees to a bole height having a six-inch inside-bark diameter. Scribner board feet log volumes are expressed as the sums of sixteen-foot logs from a single trees. The Scribner sixteen-foot log rules are generally used east of the Cascade Crest and in California. The Diamond Lake pine mushroom management area lies geographically just west of the Cascade Crest. With the exception of Pacific silver fir, the commercial tree species at the site are commercial timber species typical east of the Cascade Crest and in northern California.

Scribner volumes are useful for estimating timber harvest and production costs. Region 6 of the U.S.D.A. Forest Service historically has estimated costs of logging, transportation, manufacturing, and post-harvest site restoration per thousand board foot volumes of harvested wood. Board foot tallies are transferred to WOODPRICES (see section 4.4.16.) for estimating production costs whenever harvests occur.

Scribner board foot values are calculated in a two-step process. First, the cubic volume of a tree bole to a six-inch diameter inside bark is calculated from the cubic volume to the bole height having a four-inch top. Then, cubic volume to a six-inch top is multiplied by an empirically derived factor based on the "tarif" variable and tree diameter to derive the Scriber board foot volume. In the current version, trees with less than seven inches dbh, the standard minimum dbh for timber merchantability, are excluded from consideration during calculations for Scribner volume. This is the single departure from inventory methods used by the Pacific Northwest Research Station. Research inventories have used traditionally a 22.5 cm (8.8 in) lower diameter limit for calculating Scribner volume.

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4.6. Appendix: Computer Files for Program Source Code and Glossary of Computer Variables

The QBasic computer source code for the program MUSHROOM is reproduced in the file MUSHROOM.BAS on the diskette included with this copy of the thesis. A text copy of the program is also reproduced as an ASCII-formatted file, MUSHROOM.TXT. People using other computer languages can convert the ASCII text of the desired prescription into their computer software text editor and edit the text to conform with the syntax of other computer languages.

A glossary of all the variables used in MUSHROOM is also included on the diskette in the file GLOSSARY.DOC, formatted in WORDPERFECT 6.1. This glossary aids the user in understanding the use and occurrence of all variables used in MUSHROOM.

5. Management Experiments for High-Elevation Agroforestry Systems Jointly Producing Pine Mushrooms (*Tricholoma magnivelare* (Peck) Redhead) and High-Quality Timber in the Southern Cascade Range

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Abstract

Experimental prescriptions compare agroforestry systems designed to increase financial returns from high-elevation stands in the southern Cascade Range. The prescriptions emphasize alternative approaches for joint production of North American pine mushrooms (also known as American matsutake) (*Tricholoma magnivelare*) and high-quality timber. Other agroforestry by-products from the system are ornamental conifer boughs, pine cones, and Christmas trees. Management practices concentrate on increasing the physiological efficiency and vigor of trees, and on altering leaf area index, tree species composition, and stand age-class structure to increase pine mushroom reproduction. Programs of thinning and branch pruning test regulating flows of energy and moisture to pine mushroom mycelia in the upper soil. Experimental prescriptions incorporate monitoring to evaluate ecosystem responses to management and to accelerate adaptive learning.

Key words: *Abies amabilis*, *Abies magnifica*, adaptive management, agroforestry systems, Cascade Range, non-timber forest products, Oregon, *Pinus contorta*, *Pinus monticola*, prescription experiments, tree pruning, *Tricholoma magnivelare*, *Tricholoma matsutake*, *Tsuga mertensiana*, Umpqua National Forest, volcanic soils.

5.1. Introduction

Growth in the international trade in North American pine mushrooms (*Tricholoma magnivelare* (Peck) Redhead) from forests in the Pacific Northwest to markets in Japan (Weigand 1997b) has prompted forest managers to consider silvicultural practices that increase commercial production of pine mushrooms. Interest in this new source of forest revenue comes at a time when publicly-owned forests are subject to greater timber harvest constraints and timber revenues are lower than in previous decades. One obstacle to increasing pine mushroom production is the absence of a tradition of pine mushroom management in North America. By contrast, pine mushrooms of the closely related species *Tricholoma matsutake* have been managed for centuries in East Asia (Totman 1989, Hosford and others 1997 in press). Agroforestry technology developed for pine mushroom culture in Japanese, Korean, and Chinese forests may be useful in several North American forest types, particularly forests comprised of *Pinus contorta* (Pilz and others 1996), *P. banksiana* (Miron 1994), and *P. ocote* (Villarreal 1993).

A network of pine mushroom management areas has been established in Washington and Oregon to study the ecology and productivity of pine mushrooms (Hosford and others 1997 in press). Sites represent a broad spectrum of habitats from sea level to 1800 m elevation. Wide distribution over many climate and vegetation zones suggests that pine mushrooms may have evolved different physiological responses to local conditions. An important zone of high natural productivity and concentrated commercial harvest of pine mushrooms straddles high-elevation forests on both east and west slopes of the southern Cascade Range in Oregon. The region is noteworthy for its harsh climate, volcanic activity, ash and pumice soils, and low tree growth (Hobbs and others 1992). Knowledge of the site-specific autecology of pine mushrooms, however, remains fragmentary.

This report focuses on incorporating experimental design into stand prescriptions that combine timber management and pine mushroom culture. Designing easy-to-execute experiments within management activities can test means to increase commercial harvests of pine mushrooms and provide new information about pine mushroom management. Traditional management for pine mushrooms in East Asia are best suited to low-elevation, single-species, even-aged stands receiving summer rain. Uncertainty about appropriate management for pine mushrooms in high-elevation, multi-species, uneven-aged stands in the Cascade Range underscores the need for experimental prescriptions designed to clarify direction in pine mushroom management. Risk from innovation to net economic yields of forest products is alleviated by concurrently managing timber resources for improved tree vigor and timber quality. Examples here illustrate potential experimental management at the Diamond Lake pine mushroom management area in the Umpqua National Forest, Douglas County, Oregon.

5.2. Physical Environment of the Diamond Lake Pine Mushroom Management Area

5.2.1. Location and Topography

The Diamond Lake pine mushroom management area is located just west of the Cascade Range crest in southern Oregon at 43°12' 7"N latitude and 122°12' 20"W longitude, about 5.8 km northwest of the north end of Diamond Lake. Elevation ranges from 1675 to 1750 m. Slopes within the management area range from flat to 23 percent. Aspect varies from northwest to east. The site is shielded from prevailing southwest winds and resulting windthrow, a prominent phenomenon at other productive pine mushroom sites nearby.

5.2.2. Soils

The management area lies northwest of the Crater Lake caldera in the zone of thick deposits of volcanic ejecta following the explosion of Mt. Mazama 7,000 years ago (Carlson 1979). Other volcanos in the immediate vicinity are Mt. Thielsen (2780 m) and Mt. Bailey (2550 m). Surface soils in the study site are Cryands, loamy sands originating from Mazama ash and pumice deposition. Glacial debris is occasionally mixed in with the volcanic material, but andesite rock with good porosity underlies topsoil at variable depths (Radtke and Edwards 1976).

Litter and humus layers are generally less than 3 cm deep except on steeper, moister, north-facing sites where stands of Pacific silver fir (*Abies amabilis* Dougl. ex Forbes) and mountain hemlock (*Tsuga mertensiana* (Bong.) Carr) are often dense. Surface soil layers are low in organic matter and clay compounds (U.S. Department of Agriculture, soil inventory database samples S82-OR-019-002 and S91-OR-019-002), in stark contrast to high-elevation volcanic soils in Japan (Kawata 1981, Shoji and others 1993) and elsewhere in the southern Cascade Range (Alexander 1993). The prevailing trend of increasing organic litter with increasing elevation does not apply to the Diamond Lake management area.

In contrast with other Cryand soils in the Cascade Range, soils in the pumice and ash zone have lower available phosphorus and higher porosity (Meurisse 1987). Soil bulk density at the Diamond Lake management area is 0.75 g cm^{-3} or less. Water infiltration and permeability are both very rapid. These features may be altered somewhat when hydrophobic char remains on the soil surface after fires. Water holding capacity is low because fine pore spaces are few.

Unique physical properties of pumice-derived soils include resistance to compaction and low rates of heat storage and heat transfer, particularly during drought months (Meurisse

1987). Temperature can fluctuate widely at the soil surface, often exceeding 70 °C (Carlson 1979, Cochran and others 1967, Palazzi and others 1992) during the day and below freezing at night, even during summer months. Insulating properties of the mineral soil damp penetration of diurnal energy fluxes into soil layers when the soil is dry. Low thermal diffusivity also causes soils to warm slowly in the spring (Cochran and others 1967). Average summer temperature of soils in the area is 14 °C (Kimble 1993).

5.2.3. Climate

High-elevation forests west of the Cascade Crest in southern Oregon have a modified montane Mediterranean climate (Redmond 1992) and fall within the high winter precipitation zone in the southern Cascade Range. Most precipitation falls as snow. Summer rainfall is sparse, usually the result of local thunderstorms. Annual precipitation for the site averages 1525 mm.

5.2.4. Vegetation

Five conifer species dominate the overstory at the study site: Pacific silver fir, Shasta red fir (*A. magnifica* A. Murr. var. *shastensis* Lemmon), lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *murryana* Engelm.), western white pine (*P. monticola* Dougl. ex D. Don) and mountain hemlock. At lower elevations within the management site, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and white fir (*Abies concolor* (Gord. et Glend.) Lindl.) occur sparsely. Of the major species, *A. amabilis* and *P. monticola* appear not to form mycorrhizae with pine mushrooms in the management area.

The dominant plant association type (Atzet and others 1996) is *Tsuga mertensiana / Vaccinium scoparium* Leib., which has one of the lowest stand basal area densities of forest types in the Pacific Northwest west of the Cascade Crest. Stands within the study site have uneven-aged structure with the exception of even-aged patches of lodgepole pine, particularly in disturbed or moist, frost-prone areas. Shrub, forb, and grass species diversity is low, as is the percent cover of understory vegetation. Prominent non-tree species in the understory and in gaps include *Arctostaphylos nevadensis* Gray, *Castanopsis chrysophylla* (Dougl.) A. DC var. *minor* (Benth.) A.DC., *Ceanothus prostratus* Benth., *Chimaphila umbellata* (L.) Bart., and *C. menziesii* (R. Br. ex D. Don) Spreng. Fungi species at the sites has not yet been compiled.

Flat or gently-sloping terrain make regeneration difficult because of frequent frosts. Clearcut gaps greater than eight hectares are difficult to regenerate either naturally (Atzet and others 1992, Franklin and Smith 1974) or with planting (Halverson and Emmingham 1982). Advance regeneration, except for shade-intolerant lodgepole pine, usually responds well to small gap openings (Cromack and others 1991). Suppressed small trees in the understory, particularly Pacific silver fir trees, may be forty or more years old.

5.3. Key Management Concerns

Few silviculturists have attempted intensive management for timber production at high-elevation sites in the zone of Mt. Mazama pumice and ash deposition. Establishing economically desirable but poorly-adapted species, such as Douglas-fir, and clearcutting at high elevations retards stand regeneration and growth (Halverson and Emmingham 1982). Small gap disturbances (Cromack and others 1991) are more typical of the characteristically uneven-aged structure of high-elevation forests in the Cascade Range, especially on flat or on moister north-facing slopes. Advance regeneration also responds well to overstory removal (Helms and Standiford 1985, Tucker and others 1987).

Susceptibility of most tree species to one or more persistent plant parasites and fungal and insect pathogens requires vigilant stand tending to promote tree growth. Necessary investments for sanitation cuts, site preparation, tree planting or seeding, and pre-commercial thinning for spacing usually exceed expected discounted revenues. Plantings of preferred species grow poorly, if they survive, and less-preferred species that regenerate naturally grow slowly. Sole focus on timber as the source of revenue from high-elevation stands overlooks options for joint production such as the combining pine mushrooms and timber.

Also, Grier and others (1989) point out that investments in forest stands should not be based just on net primary above-ground productivity. Sites that yield products with disproportionately high economic value per unit of biomass may in the long run be more advantageous to manage, on one hand, and may garner broader public support for intensified management as well. Both forest incomes and forest structure can be maintained. Mixing crops with different harvest intervals also helps to even out flows of income at the scale of a stand. Stand-level even flow of resource benefits is a fundamentally different notion from even flow of timber income from annual harvesting of a fixed-percentage of a forest landscape. Nearly annual crops of wild mushrooms, of triennial boughs crops, decadal crops of Christmas trees, and partial timber cuts every 25 to 50 years may extract commercial biomass at a higher average annual rate than intensive management of a single timber crop. Investing in a suite of valuable crops, such as high-quality western white pine timber and pine mushrooms, with long histories of consumer demand globally, cushions uncertainty about future markets and management costs.

Management for pine mushrooms in high-elevation stands remains risk-laden because there is no indigenous tradition of mycoforestry based on centuries of refinement through trial-and-error. Managers need to have options in the event that assumptions underpinning novel management for pine mushrooms fail to hold up in practice. Failureresistent management in the Pacific Northwest mixes comparatively secure knowledge about timber species, based on a history of management and research, with experimental alternatives based on extrapolations from other ecosystems and adaptive learning through small-scale experimentation and monitoring.

The pine mushroom management area at Diamond Lake is challenging because species diversity and biological productivity are both low. Emphasizing individual management activities that improve quantities or qualities of several resources at once can make management more efficient and lucrative. Interventions that mimic disturbance regimes natural to the ecosystem are likely to speed recovery of ecosystems without hiatus in ecosystem productivity. Smaller-scale disturbances are also less likely to disturb the amenity values of high-elevation forests because the forest structure remains relatively unmodified or rebounds quickly.

Another set of management experiments, not discussed here in depth, but just as important to the success of stand management of high-elevation agroforestry systems, would develop a workforce and new institutions to handle new agroforestry products (Everett 1996). Multi-product management described here is more labor-intensive than traditional timber-based extraction. Improved links between non-traditional ecosystem products and their markets are needed. Programs for certification of sustainable harvests and establishment of cooperative or community-based institutions must parallel the development of stocks of novel non-timber forest products (Mater Engineering, Ltd. 1992). Without a secure forest-based laborforce and organized networks to distribute non-timber forest products to consumers, the justification for more intensive forest management remains incomplete.

Constraints based on societal amenity values prevent maximization of financial benefits from forest product goods. Amenity values such as aesthetics, recreational opportunities, and conservation of biological diversity are more difficult to quantify than values for

Table 5.1.-- The portfolio of potential agroforestry products from the Diamond Lake pine mushroom management area, Diamond Lake Ranger District, Umpqua National Forest, Oregon.

Product category and Product	*Estimated price per unprocessed unit in 1990 U.S. dollars*	*Source*
Foods and flavorings		
Tricholoma magnivelare	22.00 kg^{-1}	Amaranthus, pers. comm[1]
Chimaphila umbellata, C. menziesii	4.18 kg^{-1}	Miller 1988
Decorative cones		
Pinus contorta	0.75 kg^{-1}	Thomas and Schumann 1993
Pinus. monticola	1.33 kg^{-1}	Thomas and Schumann 1993
Decorative boughs		
Abies amabilis (open-grown)	0.35 kg^{-1}	Schlosser and Blatner 1996
Abies magnifica	0.35 kg^{-1}	
Pinus contorta	0.00 - 0.20 kg^{-1}	
Pinus monticola	0.25 kg^{-1}	
Tsuga mertensiana	0.00 - 0.25 kg^{-1}	
Christmas trees		
Abies amabilis (open-grown)	1.82 per tree	U.S. Department of Agriculture, Forest Service, Region 6, Fiscal Year 1996 Cut and Sold Report, RegionalAverages for species
Abies magnifica	1.82 per tree	
Wood products		
Abies amabilis	230.08 mbf^{-1}	
Abies magnifica	205.25 mbf^{-1}	
Pinus contorta	88.01 mbf^{-1}	
Pinus monticola	299.45 mbf^{-1}	
Tsuga mertensiana	234.64 mbf^{-1}	

[1]Michael Amaranthus, biological scientist, U.S.D.A. Forest Service, Pacific Northwest Research Station, Grants Pass, OR.

finance costs for augmenting stand productivity. Monitoring these interventions help evaluate whether agroforestry management practices leave stand structures and ecosystem processes intact and produce expected results.

Management with a multi-product approach emphasizes product quality for timber produced in small quantities at more frequent intervals rather than in volume, as for example with clearcutting, at long intervals followed by slow stand regeneration. Although attention to quality may produce highly desirable products from high-elevation forests, the time until harvest, upfront costs, technological changes, and changing product markets make for considerable risk and uncertainty. Initial assumptions and practices for agroforestry prescriptions will likely require periodic revision. In this way, an adaptive strategy uses new information as it becomes available to revise management during a cycle of uneven-aged management.

Effects of forest management practices on North American pine mushrooms are poorly known. Most information about responses by pine mushrooms to changing forest production of pine mushrooms include: altering stand tree species composition (Iwamura and others 1966), irrigation (Ishikawa and Takeuchi 1970), overstory thinning (Lee 1981), cutting understory shrub and forb species (Ito and Ogawa 1979), artificially covering pine mushroom colonies at fruiting time (Lee 1989), and removing organic litter from the forest floor (Hosford and others 1997).

Describing desired conditions achieved from such manipulations is as important as describing practices. Management for Asian pine mushrooms strives for a forest canopy with light gaps, a forest floor with a thin organic litter layer and sparse vegetation, and thriftily growing trees. The result is a soil environment exposed to a greater range of energy and water fluxes and a greater number of fine conifer roots close to the soil surface and available for mycorrhizal formation with pine mushroom mycelia than if natural vegetation developed unhindered.

Forest managers can create analogous environments in high-elevation forests in the southern Cascade Range where the stand structures, soils, and climate are different. For example, north-facing slopes are often favored for production of pine mushrooms in the Diamond Lake area as compared to dry southwest slopes in Japan and Korea (Lee 1983, Hosford and others 1997). South- to west-facing slopes may be too severe for commercial production in the Diamond Lake region because of summer drought. Certain practices such as cutting understory vegetation are of little concern at the Diamond Lake management site on account of the naturally sparse understory. Other environmental effects such as fire frequency are of greater concern in the Cascade Range but not significant in the high summer rainfall climate of Japan.

The tradition of pine mushroom management in East Asia serves as a point of departure from which to synthesize and test hypotheses about promising options for managing North American pine mushrooms. Basic differences in climate, soils, and tree species, however, point to the need to manage for pine mushrooms in commercial timber forests with objectives, goals, and practices adapted to local site conditions.

5.5. Management Objectives and Goals

Management for pine mushrooms strives to enhance biological productivity and rates of biological processes as the means to expand commercial production. To this end, management has four objectives:

- to improve tree resistance to pathogenic species
- to increase growth of individual trees
- to direct composition of regenerating trees to desired species and
- to expand suitable habitat for pine mushrooms.

These objectives emphasize product quality but allow for flexibility to chose the best means in response to changing economic demands in the future.

Overarching management goals for different stands within the Diamond Lake pine mushroom management area are established in alternative scenarios for the first 25-year cycle of uneven-aged management. Goals in management are highly likely to change in that time, however. Adaptive adjustments to surprises or new information necessitate flexibility that alters management for North American pine mushrooms in response to economic signals and technological advances. One hypothetical example of an adaptive change in pine mushroom management might involve efforts to regenerate Pacific silver fir if new evidence were to show that Pacific silver fir is a pine mushroom host species and creates suitable forest environments for commercial quantities of pine mushrooms. Potential advances in culturing Asian pine mushrooms under intensive domestication, on the other hand, might reduce demand for North American pine mushrooms in Japan, the major consumer market.

5. 6. Strategies Common to Experimental Treatments for Accomplishing Management Objectives

Five strategies define the direction of management of high-elevation forests for agroforestry joint production:

- adhere to known societal and ecological constraints;
- reduce populations of tree pathogens by controlling the mix of tree species in different age or diameter classes;
- reduce the presence of Pacific silver fir and increase the presence of western white pine;
- increase cycling rates for nutrients and organic matter; and
- harvest non-timber products when commercial quantities are available.

Each of these management strategies is described briefly in the following paragraphs.

5.6.1. Adhere to Societal and Ecological Constraints

Management scenarios proposed here assume that society's interests are best served in public forests by maintaining stand structure and biological diversity as well as by even flows of forest products through time. All products considered for agroforestry systems rely on forest structure and function being maintained indefinitely. No species originally in a stand are entirely eliminated from the stand. Shifts in species dominance are, however, planned as part of efforts to reduce tree pathogens and to improve the quality and quantity of economic production. The focus of regeneration is management of gaps less than a hectare. Management is designed to maintain robust old-growth trees where present and to foster diverse combinations of trees species and tree ages. To maintain uneven-aged forest structure, timber harvest operations are more complex and, therefore, more costly.

5.6.2. Reduce Tree Pathogens

Inventory records from the Diamond Lake Ranger District show multiple widespread tree pathogens in the pine mushroom management area. Management for reducing pathogen populations is directed to improve tree growth. Initial timber harvests are sanitation harvests to remove diseased or mistletoe-infested trees, to reduce drought stress on trees, and to improve growth rates for disease-free advance regeneration and subsequent natural regeneration. Initial harvests are the most extensive in the uneven-aged management program. Improved tree growth, in turn, is hypothesized to favor pine mushroom production by supplying more fine root sites for mycorrhizae-mediated carbohydrate supplies to pine mushroom mycelia. Integrating management practices for pathogen control also avoids worsening effects of one pathogen in the process of alleviating effects of another.

In the Diamond Lake region, dwarf mistletoe infestations affect growth of Pacific silver fir, mountain hemlock (both infested by *Arceuthobium tsugense* (Rosendahl) G. N. Jones subsp. *mertensianae* Hawksworth and Nickrent), and lodgepole pine (infested with *A. americanum* Nutt. ex Engl. in Gray). Diamond Lake is located just outside the range of high species diversity of *Arceuthobium* spp. at the extreme south end of the Cascade Range in northeast California. Consequently, both western white pine and Shasta red fir are largely immune to mistletoe parasitism in the Diamond Lake area (Hawksworth and Wiens 1996; Norman Michaels, silviculturist, Diamond Lake Ranger District, pers. comm.).

Alternating species composition in the overstory and understory can break cycles of infestation or infection from one cohort to the next. For example, mountain hemlock or lodgepole pine may be retained in overstories for biological and structural diversity, or for maintaining existing pine mushroom colonies. At the same time, promoting gaps and open understories composed of Shasta red fir and western white pine interrupts cycles of mistletoe infestation in the understory from *A. tsugense* or *A. americanum*. Shelterwood trees or seed trees that regenerate the three tree species infested by mistletoes are planned for harvest within five to ten years after opening gaps in the forest. Vector trees for mistletoe infestations, particularly from the control plots, are kept at least 20 m away (Hawksworth and Wiens 1996) from understory or gap regeneration of the same species in nearby experimental plots.

White pine blister rust (*Cronartium ribicola* Fisch.) and western gall rust (*Endocronartium harknessii* (J. P. Moore) Y. Hiratsuka) infect western white pine and lodgepole pine respectively and cause widespread mortality (Snellgrove and Cahill 1980, Hoff 1992). The principal measure to control fungal infection is to prune limbs of trees closest to the ground. Hungerford and others (1982), Hagle and others (1989), and Russell (1996) offer prescriptions for stocking and pruning to improve tree growth and vigor over long rotations. Lodgepole pine also benefits from stocking control and pruning (Cole and Koch 1996, Lishman 1995).

5.6.3. Reduce the Presence of Pacific Silver Fir in Stands and Increase the Presence of Western White Pine

All tree species at the Diamond Lake management area are valued timber species, but western white pine is the most valuable tree for timber production (table 5.1.). Clustered foliage and comparatively low leaf area of individual pine trees also contribute to more open stand canopies in contrast to Pacific silver fir. Pacific silver fir is the most shade-tolerant conifer in the area and creates dense stands of slow-growing trees and thick organic litter layers. Litter builds up on the forest floor in dense stands without sharp diurnal and seasonal high fluxes of solar energy on the forest floor. High leaf area indices and deeper litter layers in stands dominated by Pacific silver fir intercept inputs of energy and water into the soil. Interception at crucial times in the life history of pine mushrooms may reduce or delay water and energy transfers necessary to induce pine mushroom growth and reproduction.

5.6.4. Thin and Prune

Opening the overstory, by stand thinning and by selecting species with naturally more open canopies, permits stronger pulses of solar energy and water to reach upper soil layers at the time of pine mushroom fruiting. Thinning trees and pruning branches both reduce leaf area index, although the intensity of control is different with each practice. Thinning reduces drought stress and concentrates biomass on trees with the best prospects for financial returns or on trees promoting the best environment for pine mushrooms. Wood quality of pine species, in particular, improves and tree taper is reduced (O'Hara

1995b). Pruning to the height of the first merchantable log (5.3 m) increases value to the tree bole where the timber dimension, and therefore value, is highest. To date, no information is available about benefits of pruning *Abies* and *Tsuga* species for wood quality in the Pacific Northwest. An additional topic for original management experiments would be to overlay pruning and non-pruning treatments to randomly selected management circles in the pine mushroom management area. General pruning guidelines are presented in table 5.2. Pruning lodgepole pine trees differs from the other tree species because of its shade intolerance. Retaining more live crown is necessary for longer retention in mixed species stands.

5.6.5. Opportunistic Harvests of Non-Timber Forest Products

Harvests of non-timber forest products, including boughs, Christmas trees, and pine cones, in addition to pine mushrooms, provide opportunities to generate income that offset costs of conventional "precommercial" thinnings of young trees. Bough harvests and Christmas tree harvests reduce stand density and leaf area index. Timing of these harvests is difficult to predict in advance because existing yield models for these products are not very sophisticated (Weigand 1997a). Favorable market conditions, harvest timing, and supply availability on site are essential factors to determine feasibility of these harvests. The minimum for a commercial bough harvest is 2.2 metric tons of commercial grade boughs per hectare. Christmas tree sales are possible when the number per hectare of open-grown true firs with dbh's between 1 cm and 10 cm exceeds the retention target for that diameter class by 125 or more trees per hectare. Approximately, one in three years in the Diamond Lake area, western white pine trees have a large cone crop (Franklin and others 1974). Trees must be at least 3.0 m tall and must be sufficiently dense enough numbers to make cone collecting profitable.

Table 5.2. -- Suggested pruning guidelines for conifer species in the Diamond Lake pine mushroom management area.

For all trees species, *except* lodgepole pine:

Height Class	Pruning Height
> 2.5 m	1.2 m
> 5.0 m	2.5 m
>13.0 m	5.3 m

For lodgepole pines in stands where they comprise more than 60 percent of stand basal area:

Prune as for all other species.

For lodgepole pines in stands where they comprise less than 60 percent of stand basal area:

Prune only if trees have a crown ratio greater than 75%.

Height Class	Pruning Height
> 4.8 m	1.2 m
> 10 m	2.5 m
> 20 m	5.3 m.

Sources: Hungerford and others (1982), O'Hara (1995a, b), Russell (1995)

Table 5.3. presents pine management practices and their presumed effects for high-elevation forests. These practices are incorporated into experiments tied to practical, site-specific management at Diamond Lake.

5.7. Management Design to Accelerate Learning

An experimental management approach increases the certainty that forest managers draw valid inferences about effects of management practices. Three stands treated here exemplify stand conditions and demonstrate a range of options available to land managers for improving joint production and revenue. Data from Umpqua National Forest stands

Table 5.3.-- Outline of management practices, expected outcomes, and underlying assumptions for implementation at the Diamond Lake pine mushroom management area.

Management Practices	*Expected Outcome*	*Underlying Assumptions*
Thinning the overstory	Thinning trees improves pine mushroom production.	Open stands have faster individual tree growth and nutrient cycling. More energy and water reach the soil. Fluctuations in available water and energy are more extreme.
Pruning lower branches	Tree pruning improves pine mushroom production. Pruning improves survival of western white pine. Pruning improves the quality and value of timber.	Pruning reduces canopy interception of water and energy. Pruning branches prevents invasion of white pine blister rust. Butt logs of pruned trees produce more high-value, knot-free wood.
Integrating mushroom and timber crops spatially	Pine mushroom management and timber production from rust-resistant western white pines are compatible crops.	Pine mushrooms and their management do not affect growth and management for western white pine timber crops.
Directing tree species composition	Mountain hemlock is the best tree species to host pine mushrooms on cold, moist sites.	Mountain hemlock regenerates best in soils with an organic litter layer. Shifting stand dominance from Pacific silver fir to mountain hemlock increases production of pine mushrooms over time.
	Lodgepole pine is the best tree species to host pine mushrooms on burned sites and riparian sites.	Lodgepole pine regenerates best on disturbed, exposed surfaces. Lodgepole pine stands develop commercial pine mushroom colonies at high elevations.
	Shasta red fir is the best tree species to host pine pine mushrooms on flat, well-drained sites.	Shasta red fir dominates regeneration on flat sites with partial overstory retention. Shasta red firs host the most productive pine mushroom colonies.
Altering the organic litter layer	Increasing the amount of organic matter on the forest floor improves tree growth but depresses production of pine mushrooms.	Soil organic matter makes soil more fertile for tree growth. Thicker organic layers favor increased diversity of mycorrhizal fungi. Pine mushrooms do not compete strongly with most other fungi.

Table 5.3. -- continued.

Relying on natural regeneration	Natural regeneration of host tree species is the most cost-effective way to regenerate timber trees.	Natural regeneration produces the desired species mix for multi-product agroforestry systems.
Retaining old-growth trees	Partial cutting retains old-growth trees and sustains productivity of pine mushroom colonies.	Old-growth trees are natural foci of pine mushroom colonies at high elevations.
Piling and burning slash	Fires reduce the survival of pine mushroom colonies.	Mycorrhizae and mycelia lie near the soil surface and are damaged by fire. Concentrating slash burns to small areas minimizes negative effects of fire on pine mushroom colonies.

355, 357, and 401 are given in table 5.4. Within each stand, five replications are selected, each consisting of four plots. Each replication totals nine hectares. Plots within replications are randomly assigned to one of three prescriptions or to the control treatment with no management. Each experimental plot covers one hectare and has a 25 m-wide buffer treated the same way, using a total of 2.25 ha total forest area. The two 25 m-wide buffers between experiment plots reduce edge effects in the experiment plots. Buffers mitigate seed and spore dispersal and spread of tree pathogens from adjacent plots, particularly from control plots.

The experimental design will produce statistically valid information under constraints of natural variation in site conditions, including within stand variation, at Diamond Lake. A key feature is the irregular distribution of pine mushroom colonies in forest stands. Placement of replications is designed to assure that numbers of existing colonies, or the absence of colonies in stand 357, are similar among the treatment plots and the control plot of any one replication. Stands are uniform so that random placement of replications reproduce similar environmental conditions.

Stands 355 and 401 retain old-growth trees of host species for pine mushrooms. Each experimental plot contains 16 management circles with 25-m diameters. Figure 5.1. shows the schematic form of a plot surrounded by its buffer, and figure 5.2. depicts from overhead a pine mushroom management circle surrounded by interstitial cohorts of western white pine. Layout of management circles is designed not to disrupt the current distribution of pine mushroom colonies.

Where colonies already exist within a circular subplot, one or more "anchor" trees of host tree species are designated based on the location and pattern of previous pine mushroom fruiting. Anchor trees are foci of colonies and are retained indefinitely, potentially up to 800 years, as long as they do not infect gap and understory regeneration with pathogens

Table 5.4. -- Features of stands with management experiments at the Diamond Lake pine mushroom management area.

Stand Feature	Stand 355	Stand 357	Stand 401
Elevation (m)	1735	1705	1675
Aspect	NW to NE	NW to NE	W to NE
Slope (percent)	5	10 - 23	15
Position	ridge	mid- to bottom-slope	upper slope
Western white pine 100-yr site index (m)	29	30	23
Basal area ($m^2 ha^{-1}$)	24.6	53.4	60.1
Major overstory species	MH	SF, MH	SF
Minor overstory species	RF, WP	LP, WP	LP, WP
Understory species	all five species	SF (MH)	SF, LP
Fungal infection	WP, LP	WP, LP	WP, LP, RF
Mistletoe infestation	SF, MH	SF, MH	--
Drought stress	--	SF, MH	RF
Timber quality	poor	poor	poor

LP = lodgepole pine MH = mountain hemlock RF = Shasta red fir SF = Pacific silver fir WP = western white pine

that undermine tree growth. Individual management circles may not always have pre-existing pine mushroom colonies. Experimentation within each treatment plot involves a treatment program to maintain existing colonies and establish new colonies.

Slash disposal from timber harvests needs to minimize damage to existing pine mushroom colonies in plots and minimize any obstacles to reestablishing trees and fungal colonies. Where possible, management practices convert harvested biomass into merchantable timber, pulpwood, and decorative conifer boughs. Burning piled unmerchantable slash away from the treatment plots may be unavoidable, however.

Figure 5.1. Plot configuration of one treatment.

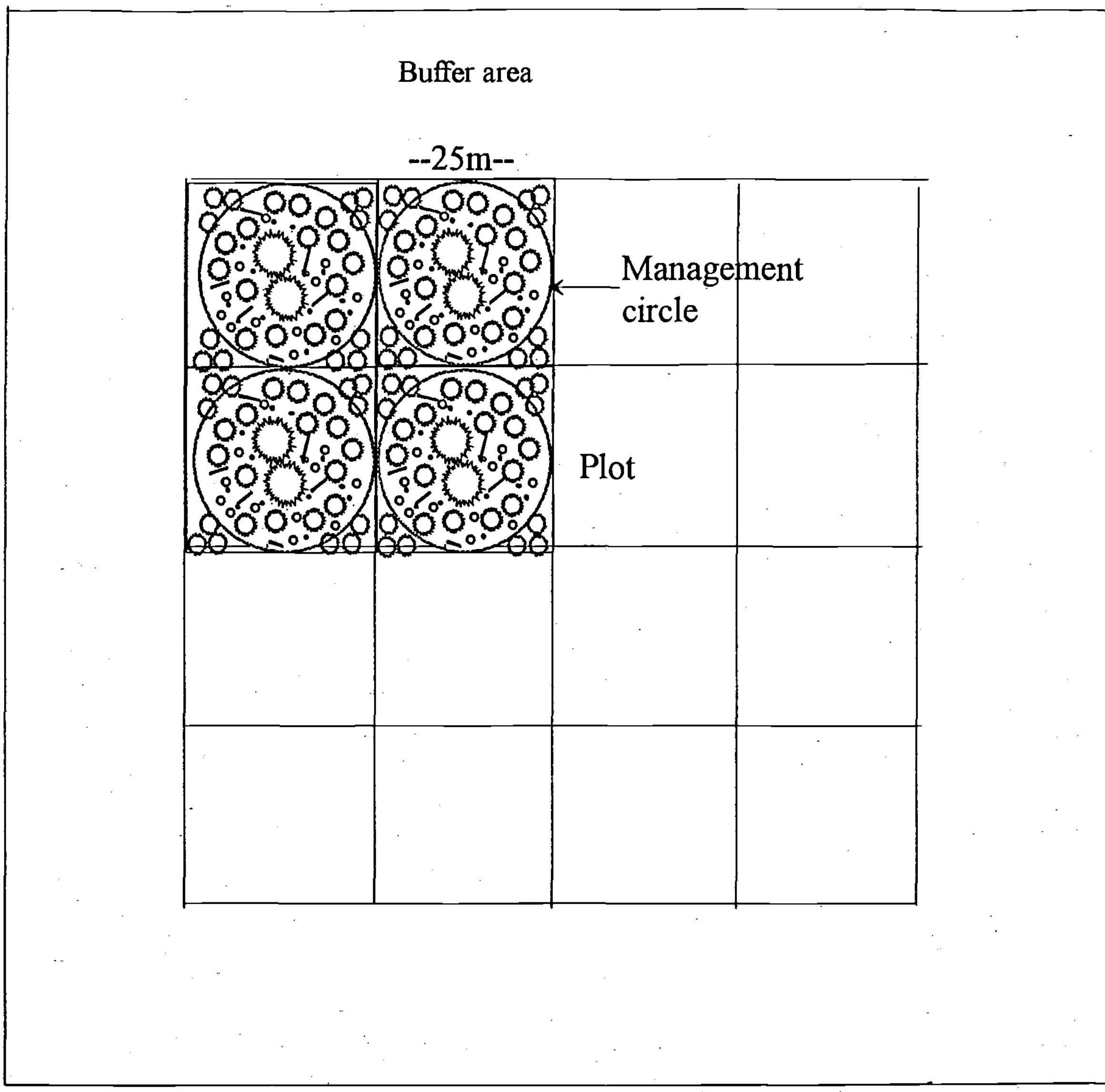
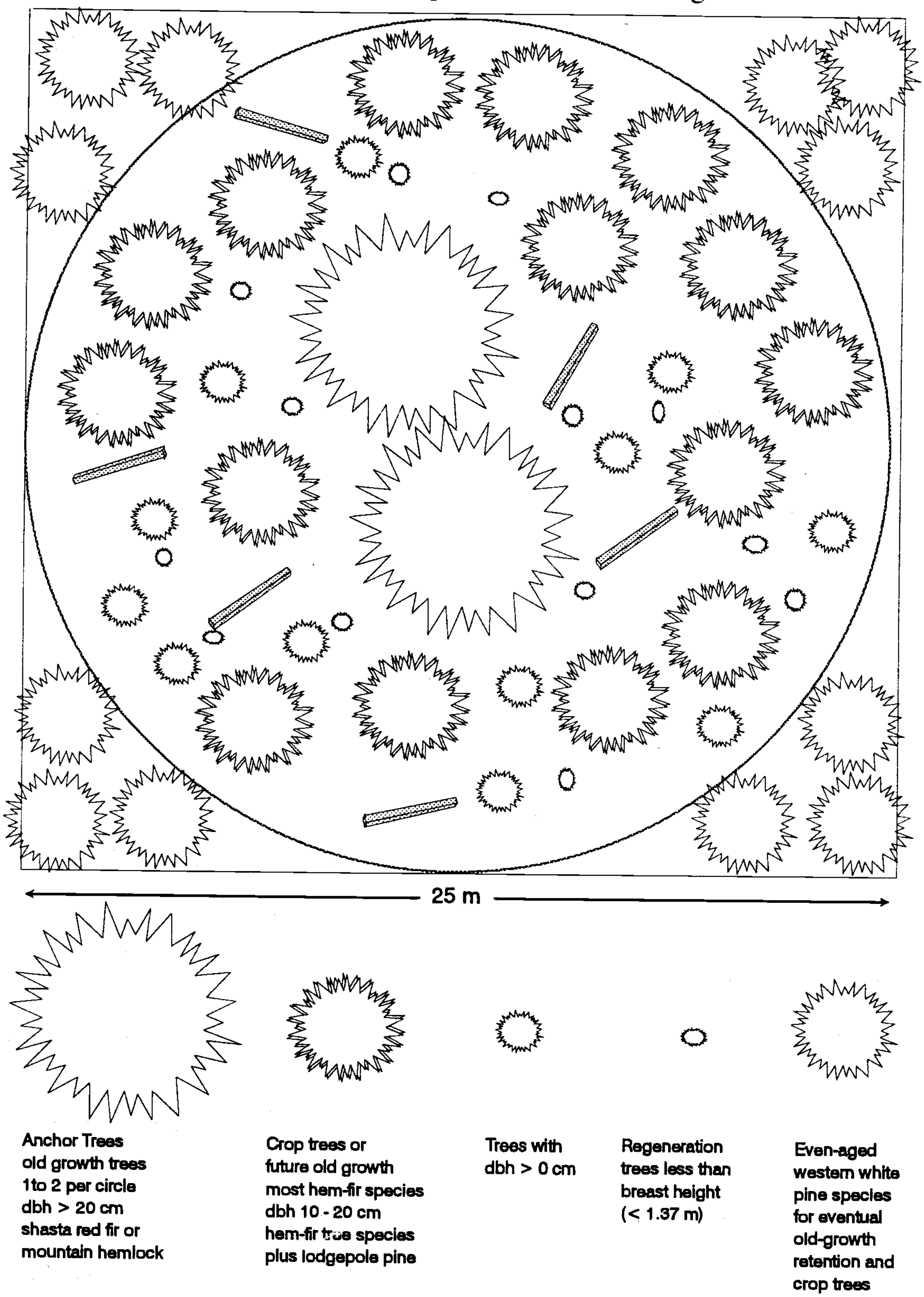


Figure 5.2. Generic scheme of a pine mushroom management circle.



No vegetation management takes place in control plots. The only direct human manipulation is annual harvests of pine mushrooms. Comparison of mushroom yields between unmanaged plots and treatment measures the efficacy of treatments to increase production. Also, in a financial analysis, the controls allow for a comparison to see whether joint production from more intensively managed plots has greater net present value than single-product harvests of pine mushrooms from control plots. If intensified management is not found to be financially feasible or socially desirable, the control plots can serve as original forest remnants that can hasten development of forest stand conditions similar to pre-management conditions.

In the interstices between management circles in stands 355 and 401, blister rust-resistant western white pine trees are planted. These trees are timber crop trees on 100-year or longer rotations with potential retention of robust old-growth trees. This effort supports regional objectives for the USDA Forest Service to restore western white pine into stands where it has disappeared after previous blister rust infections. Including western white pine is also a hedge if all efforts to manage pine mushroom colonies should fail. An important management consideration is whether western white pine trees, an apparent non-host tree species for pine mushrooms, can be grown concurrently in stands also managed for pine mushrooms. One part of the management system is monitoring the response of western white pine to stand treatments intended to augment pine mushroom production.

The role of western white pine is different in stand 357. Western white pines are planted as a row crop in combination with naturally regenerating Pacific silver fir, Shasta red fir, or lodgepole pine. Stand 357 tests whether there are sites where emphasizing timber production with non-host species (western white pine and Pacific silver fir) outweighs the combined value from timber and mushrooms in joint production. This question is especially important if managers are contemplating introducing pine mushroom colonies and their host tree species into stands where host trees and pine mushrooms were previously absent.

5.8. Vegetation Patterns Created by the Experimental Design

The Diamond Lake experiments aim to retain an uneven-aged forest structure albeit with different species composition and ratios among different age classes than might be found in control plots. Except for stand 357 just noted, the pattern of canopy development consists of even-aged cohorts of western white pine intermingling with uneven-aged management circles comprised mostly of the true firs and mountain hemlock. Lodgepole pines remain in small numbers except in one treatment each in stands 357 and 401 and in any piled slash burn sites. Plots with lodgepole pine are originally even-aged but eventually revert to an uneven-aged system as advance regeneration of different species establishes itself in the understory in the time between the second to last cut and the final cut of a lodgepole pine cohort. A shifting mosaic of uneven-aged tree cohorts results in trees growing at lower densities than might be expected in unmanaged sites. An important advantage of slow growth and low productivity of trees in high-elevations forests with ash and pumice soils is the protracted period of stand conditions beneficial to high pine mushroom production. Annual understory vegetation control of the kind typical in Japan or Korea for the understory is not required at Diamond Lake. Small-scale timber tree harvests adjust canopy structure and stand tree density every 25 to 50 years along with approximately decadal tree pruning and Christmas tree sales to extend pine mushroom production indefinitely in uneven-aged forests.

Each of the stands presented here has a different set of treatments tailored to conditions in each stand. These treatments support the broader integrated management objectives in section 5.6. Experimental variations for stands are found in following sections. Details of stand management common to all three treatments prescriptions in a stand are then described in chapter appendices.

5.9. Experimental Management for Stand 355

Objective: Converting the stand to directed uneven-aged management

Immediate goals for stand development are:

- Reduce mistletoe infestation by removing all mountain hemlock trees taller than breast height;
- Reduce white pine blister rust infections by removing all western white pine trees taller than breast height;
- Create an uneven-aged, multi-species stand that improves tree growth rates and increases in high-quality timber from western white pine in the long term; and
- Make Shasta red fir and mountain hemlock the major host species for pine mushroom colonies to increase commercial production of pine mushrooms in the near term.

Assumptions being tested:

1. Relying on natural regeneration is the most cost-effective means for regenerating the desired species composition for providing host trees for pine mushroom colonies.
2. Partial overstory removal creates and spreads pine mushroom colonies as well as increases commercial production.
3. Pruning improves forest floor conditions for pine mushroom crops, increases timber value, and improves the resistance of pine species to fungus infection.
4. Measures to improve production of pine mushrooms do not adversely affect western white pine tree growth.

Table 5.5. outlines the objectives, experimental design, hypotheses, prescriptions for agroforestry systems, and one option for incorporating further experimentation. Figure 5.3. renders a schematic cross-section of trees in treatment plots at year 25 for each of the three prescriptions for stand 355.

Outline of Prescription Variables

Prescription 1: Stand regeneration with a Shasta red fir overstory

Year 0

Harvest all trees taller than breast height except for:

up to 30 Shasta red fir trees per hectare (hereafter, tph) > 50 cm dbh, spaced with 1 to 2 trees in each management circle as "anchor" trees.

Rationale: Large trees, except for Shasta red fir, in the stand are infested with mistletoe, infected with pathogenic fungi, or have defective form. Most pathogens do not damage Shasta red fir at Diamond Lake. Cutting infected trees would remove sources of tree pathogens and permit restructuring the stand to consist of clumped overstory patches of Shasta red fir and western white pine. Residual old Shasta red firs harbor colonies of pine mushroom colonies and furnish a seed source desired for natural regeneration to reduce, in part, expenses for tree planting. Vigorous smaller Shasta red firs can respond to overstory openings for more rapid growth.

Target species for regeneration are Shasta red fir (600 tph), mountain hemlock (250 tph), and western white pine (250 tph).

Year 25

Thin to meet targets for species retention:

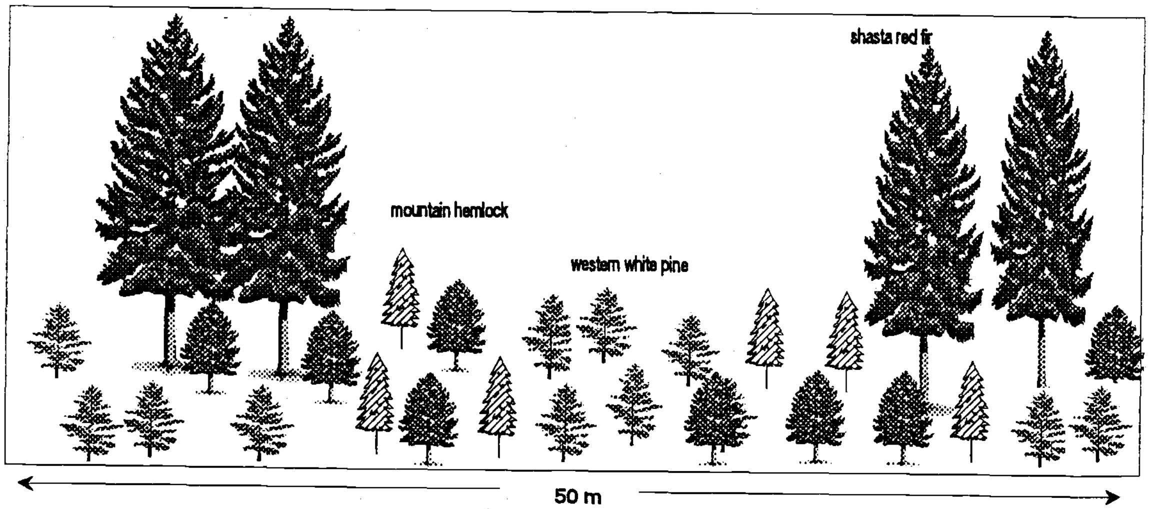
-- *Shasta red fir*

- Retain 30 to 60 tph > 50 cm dbh, two to four trees per 25 m-wide management circle
- Retain the 250 most vigorous tph between 0 and 18 cm dbh.

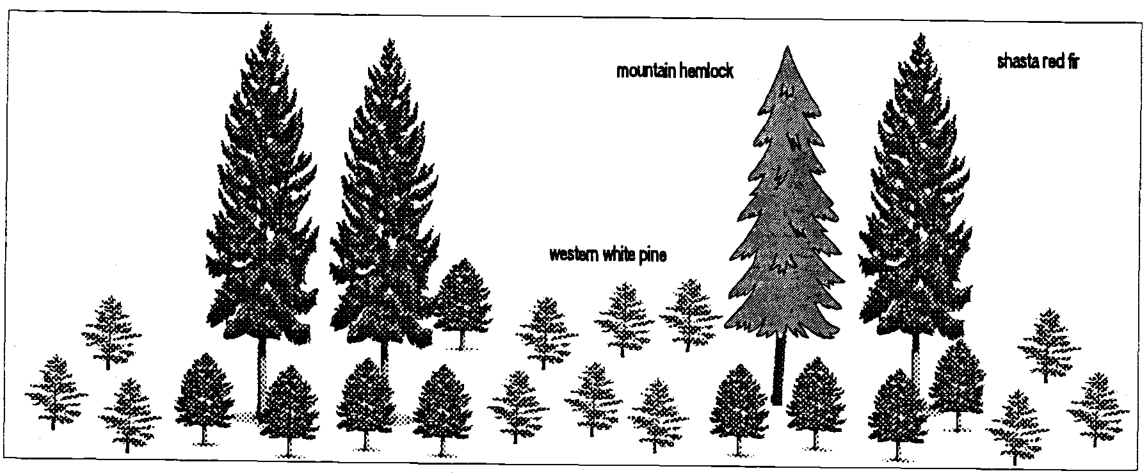
Table 5.5. -- Stand 355, Diamond Lake Ranger District - objectives, experimental design, hypotheses, and prescriptions for agroforestry systems.

Objective	**Strategies**	**Study Design**	**Hypotheses**	**Prescriptions**
Draw greater revenue from high-elevation forests.	Learn which management practices are most effective for increasing pine mushroom yields in stands dominated by Shasta red fir.	Create five replications of three treatments plus a control plot. Treatments vary the composition of species in the overstory and develop understory regeneration and further management goals to promote tree vigor.	Composition of tree species in the overstory influences the production of pine mushrooms and the vigor of colonies.	1. Retain 30 old-growth Shasta red fir tph in 16 management circles per hectare.
Constraints				2. Retain 15 old-growth Shasta red fir tph and 15 old--growth mountain hemlock tph in 16 management circles per hectare.
Maintain ecosystem processes. Retain original species diversity. Leave intact amenity values of aesthetics and recreation.	Learn which practices and which products jointly produce the highest net present value.		Species in the overstory do not affect pine mushroom production nor the vigor of colonies.	
Confine disturbances to the range and frequency of natural variation.	Learn what spatial scale of gap disturbance works best to culture pine mushroom colonies.	*Additional Option:* Randomly assign within each treatment replication a pruning / no pruning treatment on regenerating trees in eight of the 16 circles per hectare.	Density control of overstory trees and tree regeneration increases production of pine mushrooms.	3. Retain 30 old-growth mountain hemlock tph in 16 management circles per hectare.
	Learn how intensive management of mushroom colonies affects adjacent western white pines grown for high-quality timber.		Density control does not affect pine mushrooms.	4. Control plot without treatment.

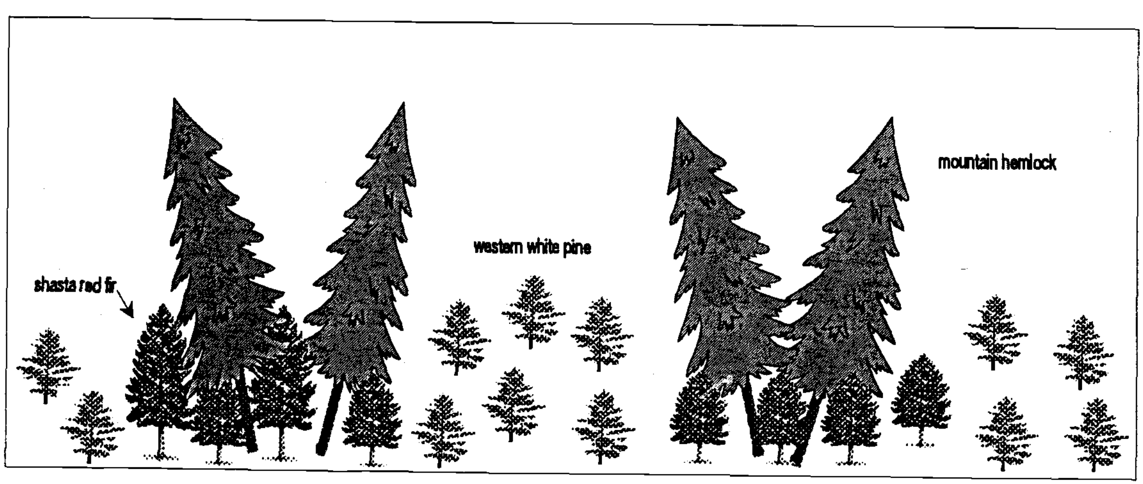
Figure 5.3. Projected stand structure for stand 355 in 25 years.



Prescription # 1



Prescription # 2



Prescription # 3

-- *mountain hemlock*

- Retain the 250 most vigorous tph between 0 and 18 cm dbh.

Rationale: Stand thinning across all dbh classes is necessary to maximize growth on individual trees and to select for trees of host species of pine mushrooms that have the greatest likelihood of advancing commercial production of pine mushrooms.

Prescription 2: Stand regeneration with a Shasta red fir / mountain hemlock overstory

Year 0

Harvest all trees taller than breast height except:

15 Shasta red fir tph > 50 cm dbh; and

15 mountain hemlock tph, with trees, regardless of species, spaced with one to two trees in each 25-m wide management circle as "anchor" trees.

Rationale: Overstory retention of old-growth mountain hemlocks and Shasta red firs may conserve long-lived pine mushroom colonies and allow for inoculation of young Shasta red fir regeneration. An understory without mountain hemlock regeneration and a small number of Pacific silver fir trees interrupts the spread of dwarf mistletoe.

Target species for regeneration are Shasta red fir (850 tph) and western white pine (250 tph).

Year 25

Thin to meet targets for species retention:

-- *mountain hemlock*

- Retain 15-30 tph > 50 cm dbh, one to three trees per 25 m-wide management circle

-- *Shasta red fir*

- Retain 15-30 tph > 50 cm dbh, one to three trees per 25 m-wide management circle

- Retain the 500 most vigorous tph between 0 and 18 cm dbh.

Rationale: Stand thinning across all size/age classes maximizes growth on individual trees and selects for host trees that have the greatest likelihood of advancing commercial production of pine mushrooms.

Prescription 3: Stand regeneration with a mountain hemlock overstory

Year 0

Harvest all trees taller than breast height except:

30 mountain hemlock tph > 50 cm dbh spaced with 2 to 4 trees in each 25-m wide management circle as "anchor" trees.

Rationale: Overstory retention of mountain hemlock and development of vigorous gap and understory Shasta red fir trees may conserve long-lived pine mushroom colonies and allow for infection of young Shasta red fir regeneration. An understory without mountain hemlock regeneration interrupts the cycle of dwarf mistletoe infestation on young trees.

Target species for regeneration are Shasta red fir (850 tph) and western white pine (250 tph).

Year 25

Thin to meet targets for species retention:

-- *mountain hemlock*

- Retain 30 to 60 tph > 50 cm dbh, two to four trees per 25-m wide management circle

-- *Shasta red fir*

- Retain the 500 most vigorous tph between 0 and 18 cm dbh.

Rationale: Stand thinning across all diameter size classes is necessary to maximize growth on individual trees and to select for host trees that have the greatest likelihood of advancing commercial production.

Prescription 4: Control plot

Years 0 through 25

No vegetation management is planned. Harvests of pine mushrooms may occur every year.

Management practices common to prescriptions 1 through 3 for stand 355 are given in the Appendix section 5.16.1.

5.10. Experimental Management for Stand 357

Objective: Shifting tree species composition and converting even-aged stand structure to an eventual uneven-aged structure.

Immediate goals for stand development are:

- Reduce the proportion of advance regeneration of Pacific silver fir in the understory;
- Produce high-quality timber with western white pine; and
- Maximize net present stand value with a single product (timber) or a combination of products (timber and either mushrooms or Christmas trees).

Management Practices Being Tested:

1. Emphasis on timber production using western white pine and a host tree species for pine mushroom colonies effectively alters stand composition for increased tree vigor and financial returns.
2. Measures to improve production of pine mushrooms do not adversely affect western white pine tree growth.
3. Tree species selection promotes pine mushroom production at sites without a history of commercial production of pine mushrooms.

Table 5.6. summarizes the objective, experimental design, hypotheses, prescriptions, and one option for add-on research for adaptive learning. Figure 5.4. portrays schematic the expected stand structure and composition crossectionally for each of the three stand management scenarios for stand 357 in 25 years.

Outline of Prescription Variables

Prescription 1: High-quality timber production based on western white pine, with delayed conversion of stand dominance to mountain hemlock and delayed introduction of pine mushroom.

This prescription changes stand structure and composition in two steps: first thinning the Pacific silver fir population and introducing western white pine; then removing a Christmas tree crop consisting mostly of Pacific silver fir and allowing natural regeneration of mountain hemlock and any Shasta red fir to dominate natural regeneration. Changes redirect stand growth to yield some economic production as soon as possible after stand management begins.

Year 0

Harvest all trees with heights greater than 1.37 m.

Harvest commercial-quality boughs from trees not intended for retention.

Rationale: The forest overstory consists of trees with little value at present and no prospect of improvement. Overstory trees are all foci of fungi pathogens or dwarf mistletoe. This radical procedure removes most of the infected or infested trees and changes the light and water status for the residual stand.

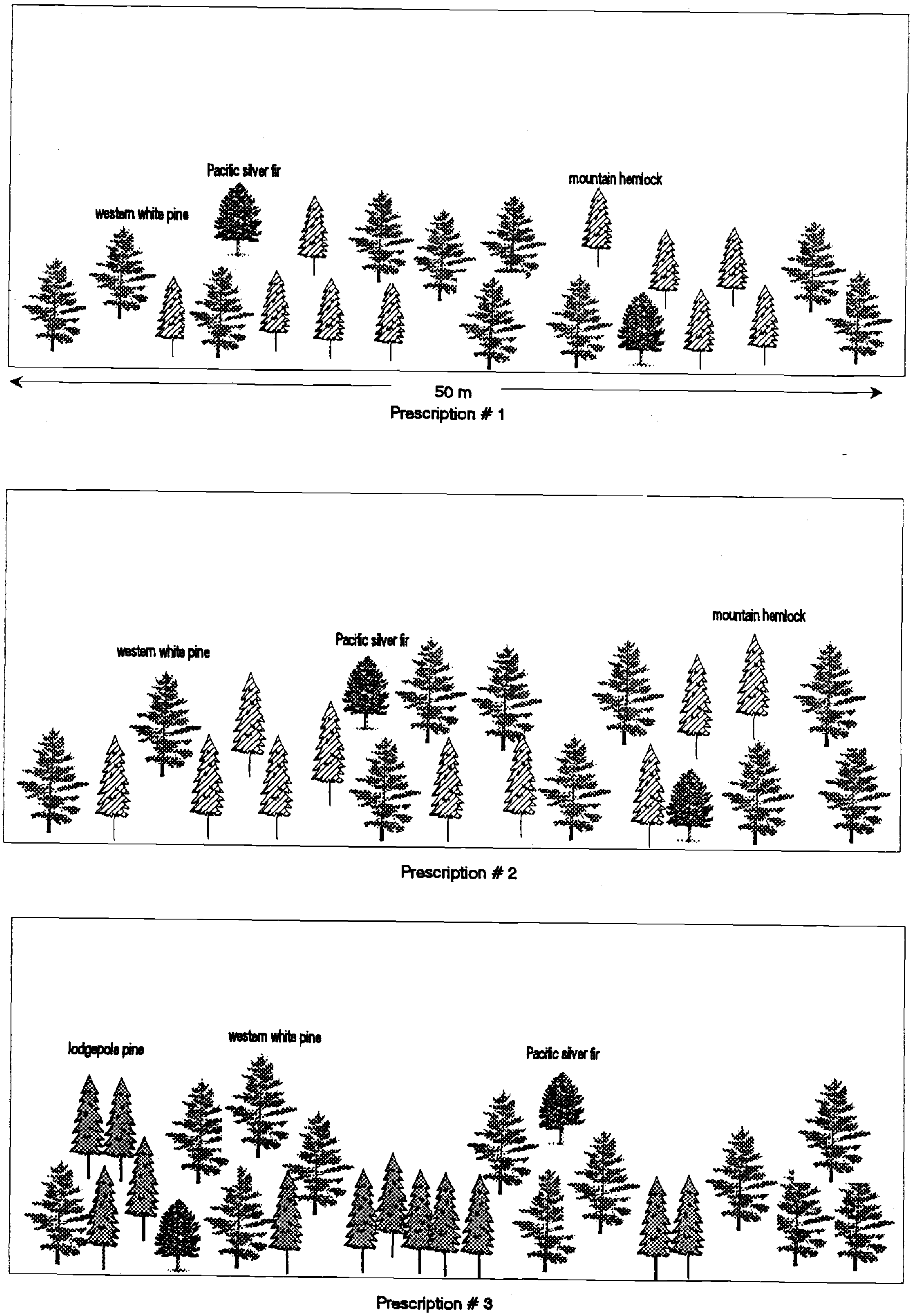
Retain 315 Pacific silver fir tph less than 1.37 m height with good spacing, the longest crowns and best form.

Rationale: Dense Pacific silver fir understory regeneration causes drought stress for these trees. By removing the overstory and reducing the density of regeneration, remaining

Table 5.6. -- Stand 357, Diamond Lake Ranger District - objectives, experimental design, hypotheses, and prescriptions for agroforestry systems.

Objective	Strategies	Study Design	Hypotheses Tested	Prescriptions
Draw greater revenue from high-elevation forests dominated now by Pacific silver fir.	Learn whether changing tree species composition introduces pine mushroom colonies into stands without previous pine mushroom production.	Create five replications of three treatments and a control plot. Treatments vary the timing, the choice of species for recomposition, and the non-timber products cropped.	Management for timber and non-timber conifer products provides the best early stand income.	1. Retain 315 tph Pacific silver firs less than breast height for harvest as Christmas trees. Regenerate with mountain hemlock seed trees.
Constraints Maintain ecosystem processes. Obtain early income from the to stand to cover costs for stand management costs. Improve biological diversity. Exclude fire as a tool to alter stand composition.	Learn which host tree species is best suited to regenerate on sites with mid- to bottom-slopes.		Management for timber and pine mushroom crops provides the best early stand income.	2. Retain 25 tph Pacific silver firs. Regenerate with mountain hemlock seed trees.
	Learn whether management of alternating generations of two host species promotes permanent pine mushroom colonies under changing stand composition.	*Additional Option:* Partition each treatment plot into 16 subplots and vary stand density of regenerating trees to test effects on timber values and mushroom crops.	Lodgepole pine is the pine mushroom host species best suited to reforest moist sites.	3. Remove all but 25 tph Pacific silver fir and mountain hemlock. Regenerate with lodgepole pine seed trees.
	Learn how intensive mushroom management affects western white pines grown for timber.		Mountain hemlock is the species best suited to reforest moist sites.	4. Control plot without treatment.

Figure 5.4. Projected stand structure for stand 357 in 25 years.



trees develop open-grown foliage. Open-grown foliage on small Pacific silver fir trees makes them potentially merchantable as decorative boughs and Christmas trees for early income from the stand.

Retain all mountain hemlocks less than 1.37 m tall.

Rationale: Favoring retention of young mountain hemlocks promotes stand dominance by mountain hemlock. Western white pine and mountain hemlock eventually predominate. Target species for regeneration are mountain hemlock (1200 tph) and western white pine (500 tph)

Year 12

Harvest Pacific silver fir trees for Christmas trees and boughs.

Rationale: Twelve-years time is hypothesized to be the time by which residual Pacific silver fir trees would bear open-grown foliage and have the merchantable size for Christmas trees Tucker and others (1987). Removing all but a few Pacific silver fir trees releases growing space for mountain hemlocks, western white pines, and any Shasta red fir.

Rationale: Stand conversion to a mountain hemlock stand with western white pine overstory may require additional mountain hemlock trees to fill gaps created by harvested Pacific silver fir.

Year 25

Thin western white pine to 300 tph.

Rationale: Thinning reduces stand density to allow more growth on remaining crop trees.

Harvest commercial-quality boughs from western white pine as well as any Pacific silver firs that are not slated for retention.

Rationale: This practice generates some income, improves health of western white pine, and reduces slash. Slash is piled and burned off-site.

Thin mountain hemlock regeneration to 625 tph, emphasizing retention of inoculated trees with good form and ample spacing.

Rationale: Mountain hemlock creates an even-aged cohort in the stand canopy. The species also serves as host trees used to spread pine mushroom colonies in the stand.

After Year 25

This stand converts to producing pine mushrooms later than the following two stand prescriptions. Commercial production of timber from western white pine and, to a lesser degree, mountain hemlock, is emphasized. In the long-term, residual trees of the current even-aged cohort of mountain hemlocks will become "anchor trees" in management circles. Following development of overstories with mountain hemlocks and western white pine, large gaps from thinnings around mountain hemlock anchor trees would promote disturbance without fire designed to promote lodgepole pine. Lodgepole pine is hypothesized to be the preferred species to replace mountain hemlock in gaps and thereby break the pattern of mistletoe infestation from overstory hemlocks to understory hemlocks. Gaps are therefore comparatively large. Slash thinnings to suppress mountain hemlocks growing under or beside canopy hemlocks may be necessary

Prescription 2: High-quality timber production based on western white pine, with prompt conversion of stand dominance to mountain hemlock and introduction of pine mushroom production.

Year 0

Harvest all trees with heights greater than 1.37 m, except for mountain hemlock trees with dbh's greater than 10 cm for use as seed trees.

Rationale: The forest overstory consists of trees with little timber value at present and no prospect for improvement. Short-term retention of mountain hemlocks as seed-trees provides, however, a seed source of mountain hemlock to reinforce a shift in understory composition to favor mountain hemlock.

Slash all Pacific silver fir regeneration less than 1.37 m tall.

Rationale: The high density of Pacific silver fir understory regeneration causes drought stress for trees. Any value for Pacific silver fir regeneration for boughs or Christmas trees is assumed to be inferior to value created from management to foster pine mushroom production and better tree growth.

Target species for regeneration are western white pine (625 tph) and mountain hemlock (1,200 tph).

Year 5

Harvest overstory mountain hemlocks that have served as seed trees.

Rationale: If seed-tree mountain hemlocks remain in the stand too long, they act as vectors for infesting the regenerating mountain hemlocks in the understory with dwarf mistletoe.

Year 25

Harvest commercial-grade pine boughs from western white pines and possibly from mountain hemlocks not marked for retention.

Rationale: This action reduces the amount of slash that is burned on a subplot in the buffer area, generates incomes from non-timber forest products, reduces stand leaf area index, and improves habitat conditions for pine mushrooms.

Thin mountain hemlock to 625 tph for retaining timber crop trees and future "anchor" trees in management circles.

Rationale: Crop trees or potential host trees for pine mushrooms are grown at wide spacing for best growth.

Prescription 3: High-quality timber production based on western white pine, with prompt conversion of stand dominance to lodgepole pine to introduce pine mushroom colonies.

Year 0

Harvest all trees greater than 1.37 m tall, except for lodgepole pines with dbh >10 cm for use as seed trees.

Rationale: A radical change in stand composition is desirable. Opening the canopy and disturbing the organic litter layer during removal of Pacific silver firs can promote lodgepole pine regeneration better than regeneration of other species.

Slash all but 25 tph each of Pacific silver fir and mountain hemlock regeneration less than 1.37 m tall.

Rationale: The high density of Pacific silver fir understory regeneration causes drought stress for trees. Any value for Pacific silver fir regeneration for boughs or Christmas trees is considered inferior to immediate implementation of vegetation management to create or improve pine mushroom productivity and better tree growth. Suppression of Pacific silver fir and mountain hemlock regeneration favors the predominance of lodgepole pines in stand regeneration.

Species targeted for regeneration are lodgepole pine (1,200 tph) and western white pine (625 tph)

Year 5

Harvest overstory lodgepole pines that have served as seed trees.

Rationale: If seed-tree lodgepole pines are retained in the stand too long, they act as vectors for infesting the regenerating lodgepole pine in the understory with dwarf mistletoe or western gall rust.

Year 25

Salvage pine boughs from western white pine and lodgepole pine trees not marked for retention.

Rationale: Income from pine boughs can offset costs of precommercial thinnings and improve timber grade quality and tree resistance to western gall rust.

Thin lodgepole pine trees to retain 600 tph.

Rationale: These trees will eventually become crop trees and residual trees can serve as focal trees for pine mushroom production.

Slash understory growth of all species, except mountain hemlock.

Rationale: Promoting mountain hemlock in gaps near clumps of lodgepole pines sets in place an eventual shift in stand composition from lodgepole pine to mountain hemlock. In this relay system of alternating stand composition, uneven-aged management with two single-species cohorts may be able to continue indefinitely which conserving pine mushroom colonies.

Prescription 4: Control plot

No vegetation management is planned. Harvests of pine mushrooms may occur every year.

Management practices common to prescriptions 1 through 3 are given in Appendix section 5.16.2.

5.11. Experimental Management for Stand 401

Objective: Conversion to directed uneven-aged management

Immediate goals for stand development are:

- Reduce western gall rust and western white pine blister rust infections in regenerating pine species;
- Create a mosaic in the landscape of predominantly single-species cohorts in each pine mushroom management circle;
- Manage Shasta red fir for uneven-aged diameter class distribution in management circles with old-growth retention;
- Manage pines species under essentially even-aged management, relying on natural regeneration.

Management practices being tested:

1. Promoting young naturally-regenerating or planted Shasta red firs around other old-growth Shasta red firs is an effective method for expanding pine mushroom colonies.
2. Relying only on natural regeneration with Shasta red fir together is a more cost-effective way to promote tree growth and augment pine mushroom production.
3. Measures to improve pine mushroom production do not affect growth of western white pines.
4. Retaining organic matter at mushroom harvest sites affects tree growth positively and depresses western white pine growth.
5. Directing the species composition leads to improved pine mushroom production.

These prescriptions have the option of leaving chipped slash on one half of 25 x 25 m subplots, randomly selected, in each treatment plot. Such practices may keep more organic matter and potential mineral nutrients on site and improve growth of trees and crops of pine mushrooms as compared to the practice of burning slash. Regeneration focuses on Shasta red fir management to produce pine mushrooms.

Table 5.7. summarizes the objectives, experimental design, hypotheses, prescriptions for agroforestry systems, and adaptive options for additional research. Figure 5.5. projects a schematic version of expected stand structure in 25 years.

Prescription 1: Pine mushroom management in uneven-aged stands predominantly of Shasta red fir and cohorts of western white pine

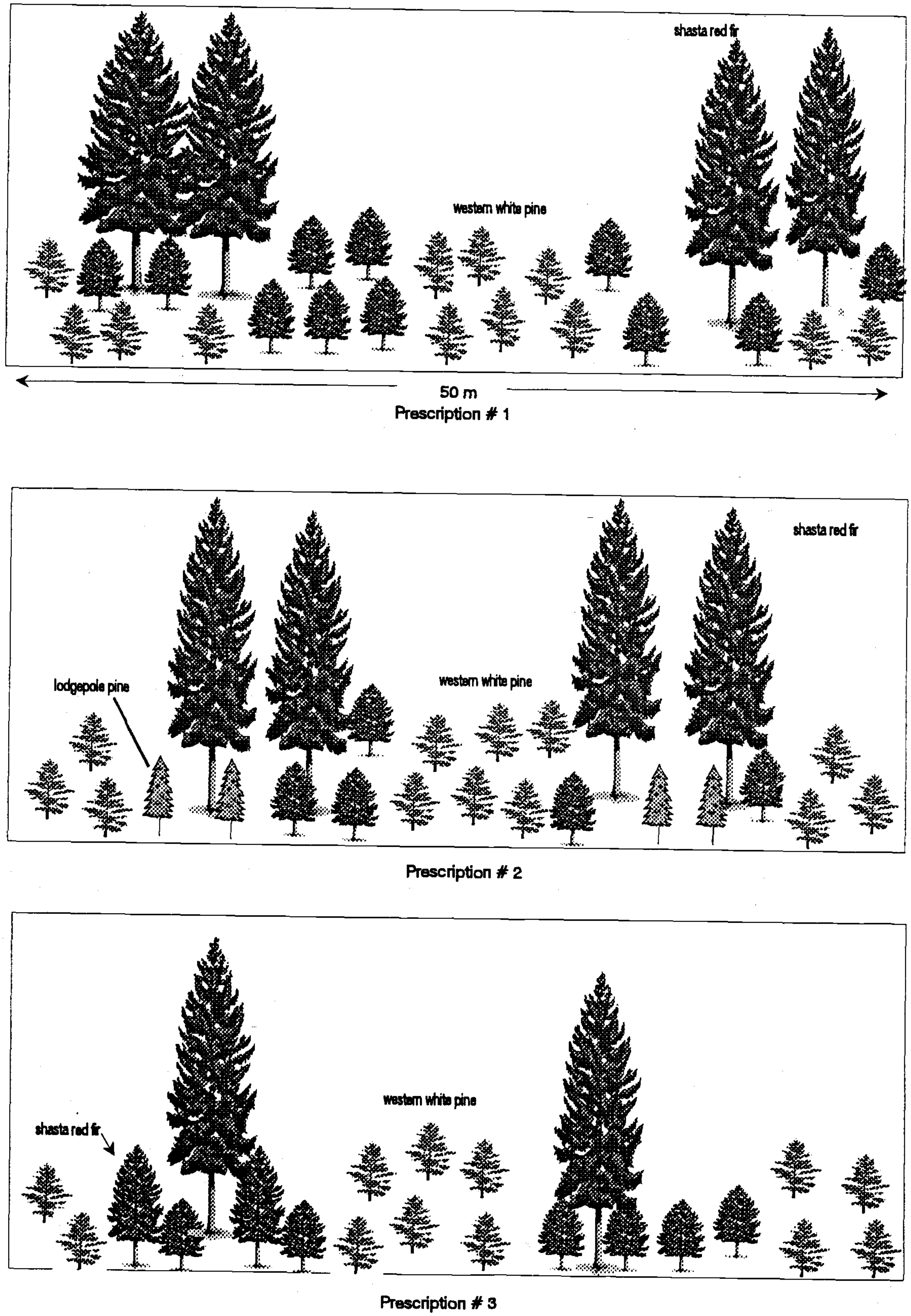
Year 0

Retain 60 Shasta fir tph with dbh's between 18 and 50 cm as seed trees.
Rationale: These trees serve a double function: retaining a cohort of mid-sized Shasta red fir in uneven-aged management within management circles and providing seed trees for natural regeneration.

Table 5.7. -- Stand 401, Diamond Lake Ranger District - Objectives, experimental design, hypotheses, and prescriptions for agroforestry systems.

Objective	Strategies	Study Design	Hypotheses	Treatments
Draw greater revenue from high-elevation forests dominated by Shasta red fir.	Learn whether pine mushroom production depends on density control of overstory trees.	Establish five replications of three treatments and a control plot. Treatments vary in the quantity of overstory canopy and the type of tree regeneration and timber products.	Shasta red fir trees spread new pine mush-room colonies faster to young trees.	1. Retain 60 Shasta red fir tph, 18 to 50 cm dbh, as seed trees; and 60 tph, >50 cm dbh, as old-growth retention.
Constraints Maintain ecosystem processes. Conserve species diversity. Retain amenity values for aesthetics and recreation. Provide habitat for high-elevation old-growth wildlife species.	Learn whether one host tree species is favored for establishing new pine mushroom colonies.		Lodgepole pine trees spread new pine mush-room colonies faster to young trees.	2. Retain 60 lodgepole pine tph >10 cm dbh as seed trees; and 60 Shasta red fir tph >50 cm dbh.
	Learn whether volume and type of organic matter from trees changes soil chemistry and inputs of water and solar energy into the soil.	*Additional Option:* Choose randomly two groups of five manage-ment circles from one treatment plot. Pile a fixed mass of organic litter collected from one group onto each circle in the second group. The remaining six circles serve as controls.	Amount of tree canopy affects production of pine mushrooms and the number of new colonies.	3. Retain 30 Shasta red fir tph, 18-50 cm dbh as seed trees; and 30 Shasta red fir tph >50cm for old-growth retention.
	Learn whether the volume of organic matter affects production of pine mushrooms.		Amount of tree canopy has a neutral effect on pine mushrooms.	4. Control plot without treatment.

Figure 5.5. Projected stand structure for stand 401 in 25 years.



Retain 60 Shasta red fir tph with dbh's > 50 cm with 2 to 4 trees per 25 m-wide management circles as anchor trees.

Rationale: Old-growth Shasta red fir trees may be the foci of pine mushroom colonies. These trees maintain habitat for high-elevation old-growth wildlife species. Although old Shasta red fir trees may be deformed and have little merchantable value as timber, they are more resistant to fungal, insect, and parasitic plant pathogens than old trees of other species and better protect younger-aged cohorts from pathogen species.

Harvest commercial-quality boughs from lodgepole pine regeneration and any excess Shasta red fir regeneration.

Rationale: Harvesting boughs reduces leaf area index and generates some income to cover management costs. These practices reinforce virtually exclusive Shasta red fir regeneration.

Chip unmerchantable slash and

Leave slash on site.

Rationale: Slashing non-merchantable lodgepole pine and excess Shasta red firs reduces competition for growing space among trees and suppresses lodgepole pine regeneration to favor Shasta red fir.

Target species for regeneration are Shasta red fir (1,200 tph) and western white pine (250 tph).

Year 5

Harvest Shasta red fir seed trees between 18 and 50 cm dbh.

Rationale: Seed trees are removed so that treatments in each prescription are parallel and to provide more growing space for regenerating trees.

Prescription 2: Pine mushroom management in uneven-aged stands with Shasta red fir canopy, lodgepole pine filling gaps, and cohorts of western white pine.

Year 0

Retain 60 tph lodgepole pines with > 18 cm dbh as seed trees.

Retain 60 Shasta fir tph with > 50 cm dbh, with 2 to 4 trees per 25 m-wide management circles as anchor trees.

Rationale: Lodgepole pine is the target regeneration species. Opening the canopy creates more suitable growing space for lodgepole pine, which can host new pine mushrooms colonies.

Harvest Shasta red fir regeneration as Christmas trees, if feasible.

Harvest boughs of natural regeneration of Shasta red fir or excess lodgepole pine stocking.

Rationale: This treatment emphasizes regeneration of lodgepole pine at the expense of Shasta red fir. Initially regeneration of Shasta red fir is removed. Additional income for stand management comes from boughs and Christmas trees from the excess Shasta red fir trees.

Slash remaining non-merchantable Shasta red fir regeneration to favor only lodgepole pine regeneration.

Target species for regeneration are Shasta red fir (600 tph), lodgepole pine (600 tph), and western white pine (250 tph)

Year 5

Harvest lodgepole pine seed trees.

Rationale: Western gall rust has infected lodgepole pine trees in the stand overstory. Continued retention of the overstory trees would increase the chance of passing gall rust infection to understory regeneration.

Year 15

Thin for spacing to leave 40 lodgepole pines for each management circle, totaling 640 tph and favoring the most robust trees.

Prescription 3: Pine mushroom management in stands with Shasta red fir canopy, and Shasta red fir filling gaps, and cohorts of western white pine.

Year 0

Retain 30 Shasta red fir tph, with dbh's between 18 and 50 cm, for seed trees evenly distributed across the stand.

Retain 30 Shasta red fir tph with >50 cm dbh, with 1 to 2 trees per 25 m-wide management circles as anchor trees.

Rationale: Shasta red fir may be the preferred species for natural regeneration, but densities of overstory retention and seed trees may not need to be as high in Prescription 1 for suitable tree regeneration and commercial pine mushroom production.

Slash and **chip** remaining non-merchantable Shasta red fir regeneration to favor only lodgepole pine regeneration.

Leave chips on site.

Rationale: Slashing non-merchantable lodgepole pine and excess Shasta red firs reduces competition for growing space among trees and suppresses lodgepole pine regeneration to favor Shasta red fir.

Target species for regeneration are Shasta red fir (1,200 tph) and western white pine (250 tph).

Year 5

Harvest all seed trees of both species.

Rationale: Seed trees of both species are removed to avoid infection of young trees and give young trees space to grow faster.

Plant per hectare twice the number of seedlings lacking of target species if natural regeneration does not meet two-thirds of the targeted amount of regeneration.

Year 15

Salvage boughs and **slash** lodgepole pine and Shasta red fir to reduce stand density to a maximum 640 tph (40 trees per management circle) of the most robust regenerating trees, regardless of species.

Rationale: Spacing affords more rapid growth of remaining. By not specifying how much of each species must remain, the manager has discretion to adapt the regeneration to site conditions in and around each management circle.

Prescription 4: Control plot

Years 0 through 25

No management is planned. Harvests of pine mushrooms may occur in every year.

Management practices common to prescriptions 1 through 3 are given in Appendix 5C.

5.12. Monitoring response variables

Improving future yields and financial benefits from multiple forest products is contingent on a continuing flow of information from treatment and control plots. The proposed monitoring program assures that quantitative information is collected to support or refute the assumptions underlying scientific forest stand management. Response variables include both economic and ecosystem variables (table 5.8.). If none of the alternatives proves to be economical and cannot attain goals at any time during the first 25 years, practices need to be reevaluated and redesigned.

Table 5.8.: Response variables, techniques for sampling, and response variables units for management experiments at the Diamond Lake pine mushroom management area.

Response variable	*Technique*	*Units*
	------ Financial Variables ------	
pine mushroom production	simulated commercial collection	kg ha^{-1}
value of mushroom harvest	recorded mushroom sale tickets	US \$ ha^{-1}
timber harvest	recorded timber scale tickets	mbf ha^{-1}
timber harvest value	recorded timber scale tickets	US \$ ha^{-1}
commercial bough harvest	recorded bough sale receipts	tonnes ha^{-1}
commercial bough value	recorded bough sale receipts	US \$ ha^{-1}
pine cone crop mass	recorded cone sale receipts	kg ha^{-1}
value of pine cone crop	recorded cone sale receipts	US \$ ha^{-1}
Christmas tree sales	recorded sale receipts	US \$ ha^{-1}
	------ Ecosystem Variables ------	
leaf area index	light meter readings	unitless
canopy cover	light meter readings	unitless
soil acidity	soil pH meter	pH
soil organic matter	loss on ignition	kg ha^{-1} cm^{-1}
soil litter depth	random measurement in treatment plots	cm
soil litter mass	dry weight samples of fixed area	kg ha^{-1}
soil moisture in autumn	tensiometer	g 100 g^{-1} soil
nitrogen	Kjeldahl	g N 100 g^{-1}
soil temperature in autumn	hourly thermometer readings in A1 layer	°C
stand basal area increment	dbh measurements of tree subsamples	m^2 ha^{-1} yr^{-1}
pine mushroom mycorrhizae	soil cores	number ha^{-1}
fungal species diversity	soil cores	number of species

Chen and others (1993) stress the importance of continuous monitoring with many replications among sites, environment, and weather conditions. The monitoring program outlined here, however, assumes little funding will be available and concentrates on the most critical variables. New information may indicate that omitting or adding response variables is in order.

Monitoring experimental plots includes mapping locations and densities of production in each harvest season and tracking the rate of creation and spread of selected colonies for correlation to the age, density, and species of host trees and to local environmental conditions. Understanding correlations between tree growth and pine mushroom fruit-body production will be essential to understanding synergism between timber management and wild edible mushroom management. Of particular concern is whether trees growing in stands with target conditions described here will actually grow better than in unmanaged stands. Effects on productivity from ecological interactions between trees and their mycorrhizal hosts, and pine mushrooms in particular, remain poorly known.

Soil temperature, total solar radiation, effective precipitation, and soil moisture in the A1 layer on sites with different treatments require daily, or even hourly, readings at critical times in pine mushroom life history, particularly at harvest time. These readings can provide valuable insight into short-term and small-scale factors that produce commercial quantities of pine mushrooms.

Data on energy and water energy entering the soil column is critical first to test whether changes in the canopy from tree harvesting or pruning generate the desired increases in energy and rainfall reaching the ground. Secondly, there is a need to test whether these increase in energy and rainfall at key times produce the desired stimuli in the top layer of the mineral soil to increase pine mushroom production. Tree growth in response to management can be tested by measuring leaf area index and stand basal area. An important question is whether improved growth of trees actually promotes fruiting of pine mushrooms.

Multiple readings at randomly chosen points within treatments plots need to account for variability within a plot for a more complete understanding of variation within plots. A minimum of thirty-five readings per treatment plot is advised.

5.13. Opportunistic Research

Investments in future forest production are susceptible to risks. Climate change and catastrophic fire, for example, are events that could nullify the best-planned management. One form of disaster-preparedness is institutional commitment to tracking response and recovery to human-induced micro-disasters. Important information about pine mushroom ecology and the ability of pine mushrooms to recolonize burned sites can be found where slash residue from harvests in the pine mushroom management area has been piled and burned. Taken together, the sites furnish a database for analyzing and developing disturbance response to fire.

Researchers in Japan and Taiwan are already reporting advances in inducing mycorrhizae in vitro between Asian pine mushrooms and both *Pinus resinosa* (Eto 1990) and *Pinus taiwanensis* Hu (1995). Eventual success with similar artificial propagation using North American pine mushrooms and host tree species seems inevitable although initial efforts have been unsuccessful. "Domestication" of pine mushrooms means, of course, that the supply of Asian pine mushrooms might grow swiftly. On the other hand, an increasingly important advantage for the Pacific Northwest in coming decades is the large base of public forest lands in the Pacific Northwest. Pine mushroom crops from North America's native forests can meet rising demand from increasingly affluent East Asian countries and contribute even to world-class tourism targeted to mushroom hunters. The need to research and refine pine mushroom propagation and to plan stand-level culturing trials as management experiments is likely to meet needs of commercial and recreational pickers.

5.14. Conclusion

The function of the prescriptions presented here is not advocacy for straightforward implementation of fixed prescriptions. More important to forestry and foresters is the notion that management for valued pine mushroom crops and high-quality timber is possible; foresters already have the silvicultural tools to implement treatments designed to further the ecological understanding of pine mushroom culture. The reward, of course, can be in terms of the increased revenues from stands. Not least, though, is the sense of satisfaction for foresters from integrating research results, personal knowledge about the ecosystems that they manage, and questioning "what ifs" to come up with creative *and* practical adaptive management experiments suited to the ecological conditions of forests under their management.

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5.16. Appendices

5.16.1. Management Practices Common to Prescriptions 1 through 3 for Stand 355.

Year 0

Harvest commercial-grade boughs on trees not planned for retention.

Harvest boughs to specified heights on all retention trees.

Rationale: Boughs from trees to be harvested may yield enough commercial biomass before boles are harvested and thereby reduce slash disposal. Merchantability will depend on the species composition, demand for specific species, and size of trees. Non-merchantable biomass is piled and burned off-site.

Harvest all western white pine, taller than breast height.

Rationale: Eliminating larger western white pines removes trees infected with western white pine blister rust.

Plant 240 tph blister rust-resistant western white pine stocks in cohorts of fifteen between pine mushroom management circles.

Rationale: Western white pine is the most valuable timber species native to the research site. Per hectare, 16 cohorts comprised of 15 seedling trees are planted at 25 m intervals in the interstices of pine mushroom management circles. Western white pine are managed on a 100-year or longer rotation, with some old-growth retention trees eventually left on site.

Retain non-target species for stand species diversity as follows:

60 tph lodgepole pines less than breast height and

60 tph Pacific silver firs less than breast height.

Year 5

Plant per hectare twice the number of seedlings lacking of target species if natural regeneration does not meet two-thirds of the targeted amount of regeneration.

Year 15 (approximate)

Harvest boughs from western white pine and lodgepole pine trees > 2.4 m height to

1.2 m high, to prevent blister rust and gall rust infection; also prune other species where appropriate according to pruning guidelines.

Rationale: Pruning accomplishes several benefits simultaneously for stand productivity. First, pruning inhibits infection from blister rust in the lower branches of a tree's live crown that lie close to the ground (Russell 1995). Early pruning of young trees also produces lumber of higher quality at harvest because knot-size is reduced in volume, thus leaving more clear wood volume. Other benefits are the reduction of leaf area index and resulting decreased leaf litter accumulation on the forest floor. When canopy and litter interception of energy and water fluxes diminish, pine mushroom production is hypothesized to increase. Comparison with control sites serve to validate this hypothesis.

Year 25

Harvest commercial-grade boughs on trees not planned for retention as in year zero.

Rationale: Reduction of leaf area index results in less water stress, fewer nutrient deficiencies, and causes more rapid nutrient cycling.

Harvest trees to meet targets for species retention:

Pacific silver fir

Retain 60 tph shorter than breast height, giving preference to open-grown trees.

western white pine

Retain at least 125 tph, giving preference to the best-spaced, largest, pruned, blister-rust resistant trees.

lodgepole pine

Retain 60 tph taller than breast height, giving preference to healthy trees with long crown length.

Rationale: Rather than produce a large quantity of small diameter trees, stand management early on strives for fewer trees with larger diameters and better wood quality at harvest. A heavy early thinning to release the most robust western white pine trees may make additional thinnings unnecessary before the final harvest cut. Reducing the density of lodgepole pine stands is important to reduce insect and fungal infestations.

After Year 50

Harvest all but the most vigorous lodgepole pines.

Rationale: Lodgepole pines will likely not thrive in stands where old-growth trees and western white pine crop trees are targeted for best growth.

After Year 100

Harvest western white pine except for 10 tph old-growth retention trees. Plant western white pine in the same pattern as in year zero except that the interstices are off-site in a uniform direction by 5 m.

Rationale: Developing a renewable western white pine resource may take a century or more to achieve. The value of western white pine trees pruned for high-quality lumber will likely be comparable with eastern white pine (*Pinus strobus* L.) and sugar pine (*P. lawsoniana* Dougl.) (Page and Smith 1994, Fahey and Willits 1995). Also, as part of restoration, remnant large western white pine are left on site to confer old-growth features on the site.

Retain Shasta red fir or mountain hemlock trees to develop an enduring overstory of at least 30 old-growth (i.e. ≥ 50 cm dbh) trees per hectare. At year 100, middle-aged western white pines and either Shasta red firs or mountain hemlocks dominate the canopy.

Cut younger trees depending on the composition of the overstory. Stands with old-growth mountain hemlock will yield some Shasta red fir timber; stands with just Shasta red fir in the overstory emphasize cutting mountain hemlock so that younger cohorts of mountain hemlock can continue to regenerate unaffected by mistletoe infestations.

Rationale: Continuity in stand density control is hypothesized to extend optimum conditions for pine mushroom colonies. This method is chosen as an alternative that simulates indefinitely mid-seral stand conditions to promote pine mushroom colonies while permanently retaining old-growth trees.

5.16.2. Management Practices Common to Prescriptions 1 through 3 for Stand 357.

Year 0

Plant 625 tph blister rust-resistant western white pine seedlings on wide 4 x 4 m spacing for stand diversity

Rationale: This enrichment planting raises the potential timber value of the stand considerably and help to redirect the stand composition away from dominance by Pacific silver fir.

Year 0 and following years

Spread pine mushroom sporocarps on and in the ground to introduce pine mushroom spores for inoculating small trees.

Year 5

Plant per hectare twice the number of seedlings lacking of target species if natural regeneration does not meet two-thirds of the targeted amount of regeneration.

After Year 25

The stand uses western white pine to guarantee high-quality timber production. Lodgepole pines, where present, are harvested after year 75. A few residual trees function as seed trees around large gaps created by harvests of midstory mountain hemlocks. Long-term uneven-aged management consists of alternating generations of lodgepole pines or mountain hemlock in the canopy when the other species is regeneration in the understory. Given the difference in shade tolerance between the two species, different methods of regenerating each species need testing.

5.16.3. Management Practices Common to Prescriptions 1 through 3 for Stand 401.

Year 0

Harvest all commercial-grade boughs from trees not marked for retention.

Rationale: Harvesting boughs generates some income to offset management costs, reduces leaf area index, and slash accumulation from harvesting.

Harvest commercial-grade boughs from trees marked for retention, according to guidelines for pruning in the main text.

Rationale: Reduction of tree leaf area and the amount of leaf litter on the forest floor is believed important for increasing commercial quantities of pine mushroom. Reduced depth of the organic litter layer can occur by removing leaf litter or by ensuring that leaf litter decomposes quickly and cycles organic matter into the soil. Here branch debris is kept from landing on the forest floor of a management circle and disposed of in a management circle designated for pile burning.

Harvest all western white pine trees taller than 1.37 m and **retain** any naturally regenerated western white pines less than 1.37 m tall in all management circles.

Rationale: As a precaution, all western white pine trees greater than breast height are removed to prevent infection in planted regeneration.

Retain vigorous Shasta red fir trees > 50 cm, with up to three anchor trees per management circles.

Rationale: Old Shasta red fir trees frequently host pine mushroom colonies. Retention of these old trees may allow for spread of pine mushroom to other younger trees growing in the vicinity of old anchor trees.

Plant 240 tph blister rust-resistant western white pine stock in the interstices of management circles

Rationale: Reestablishment of disease-free western white pine is part of a regional strategy to restore western white pine to its former ecological significance and to raise the potential value of timber in future harvests. It is also the most valuable timber species at the Diamond Lake pine mushroom research site.

Year 25

Harvest from below half of the basal area of all trees between 18 and 50 cm dbh.

Rationale: Perpetuation of uneven-aged stand composition retains the largest trees in this diameter class for recruitment as anchor trees if old trees become moribund or now longer provide pine mushroom crops.

Thin western white pines to 80 tph, retaining the most robust trees in cohorts of five trees per management circle interstice.

Rationale: This is a release thinning to allow the western white pine trees to maximize volume growth on fewer but proportionately more valuable trees. One to two prunings have already occurred by this time. Spacing between trees of western white pine cohort ranges between 12.5 m to 17.7 m.

After Year 25

The stand emphasizes timber quality and annual pine mushroom harvests under management for joint production. Eventually three diameter classes make up the stand:

- an old-growth cohort of Shasta red fir trees retained indefinitely as anchor trees for pine mushroom colonies (>50 cm dbh);
- a mid-size cohort (18 cm < dbh < 50 cm) of either Shasta red firs or lodgepole pine or both, managed for timber production on long rotations and as eventual replacement trees for any dying anchor trees; and
- understory regeneration trees.

The content of understory regeneration trees consists of lodgepole pine and Shasta red fir if the mid-size cohort is made up of only Shasta red fir. Otherwise, the understory consists of Shasta red fir alone if the mid-size cohort is made up of lodgepole pine or a mix of lodgepole pine and Shasta red fir. Both planted and naturally regenerated western white pines occur in this stand. The age class distribution of western white pine may be uneven, if gaps are colonized by naturally regenerating western white pine along with the target species.

5.16.4. Computer Source Code for Management Regimes

Each of the regimes described in this chapter are reproduced in QBasic computer source code for use in modeling with the program MUSHROOM (Weigand 1997a). The nine regimes are reproduced in the QBasic program file REGIMES.BAS on the diskette included with the copy of the thesis. Individual versions of the prescription are entitled with the word "CULTURE" plus specific suffixes that denote first the prescription number (either one, two, or three) and then the three-digit Umpqua National Forest stand number (355, 357, and 401) for the pertinent stand for the regime. For example, Prescription #2 for stand 357 is found under subprogram CULTURE2357. Note that QBasic software converts the QBasic source code of REGIMES.BAS to an ASCII-encoded file for incorporation into editors of other software programs.

6. Monte Carlo Simulations for Analyzing Feasibility of High-Elevation Agroforestry Systems with North American Pine Mushrooms (*Tricholoma magnivelare* (Peck) Redhead), in the Southern Cascade Range, Oregon, USA

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Abstract

Production of timber and non-timber forest products are simulated for three high-elevation stands with different initial compositions from the Diamond Lake pine mushroom management area in the southern Cascade Range, Oregon, USA, over the initial 25-year planning cycle. Stands are being converted to favor development of commercial crops of *Tricholoma magnivelare* (Peck) Redhead for Japanese markets. A sensitivity analysis of scenario responses to new management show that returns will continue to be high even if the Japanese gross domestic product grows at the slow pace (1.5% annually) characteristic of the 1992-1995 recession and if regionwide production from the U.S./Canadian Northwest remains at its current capacity. A change in stand-level production from a baseline to a five-fold increase in average annual production capacity at Diamond Lake within five years would raise undiscounted 25-year total income of pine mushrooms from US$44-126 (1990 dollars) to $415-959 per hectare, depending on the range of external economic factors in scenarios considered.

In some stand scenarios, the value of pine cone harvests may exceed that for pine mushroom under any pricing scenario. Bough cutting regimes proved costly and need reevaluation to avoid excessive pruning, to encourage Christmas tree crops, and to increase merchantable yield rates. Timber continued to provide the major undiscounted source of income, either from seed tree harvests or partial overstory thinnings at the end of the 25-year cycle. Scenarios promoting lodgepole pine regeneration produced the smallest end-of-cycle harvests and suggest that lodgepole pine is not a suitable species for including in uneven-aged management regimes. Under a ten percent discount rate, total revenues from joint production scenarios with non-timber forest products from the best timber-producing stand ranged from 0.43 to 1.10 times the income value of the baseline scenario, a stand clearcut in year zero. Loss of timber revenue by foregoing clearcutting and switching to uneven-aged management of naturally uneven-aged stands did not necessarily result in loss to net income. Choice of a silvicultural regime to generate both

timber and non-timber forest products plays the key role in determining yield and net value. Much work remains to be done refining regimes for maximizing financial returns from joint production.

Key words: *Abies magnifica*, boughs, Christmas trees, matsutake, net present value, Oregon, pine cones, pine mushrooms, *Pinus contorta*, *Pinus monticola*, sensitivity analysis, *Tricholoma magnivelare*, *Tsuga mertensiana*.

6.1. Introduction

The portfolio of commercial forest products from the Pacific Northwest of North America includes many non-timber products. Growth in regional, national, and global markets for non-timber forest products from the region has prompted land managers to consider options for agroforestry as one means to increase stand income while maintaining intact forests. One important question regarding non-timber forest products is whether annual or decadal harvests of these products can make up for reduced timber harvest incomes. Production of non-timber forest goods is poorly described but becomes relevant when timber rotations are extended, or when mature and old-growth residual trees are retained as forests are converted to two-aged or uneven-aged stands. These instances of management reflect scientific and public interest in conserving and re-creating forests stands with old-growth features and habitats.

Agroforestry, in particular forest farming, involves creating favorable understory environments for growing shade-tolerant specialty crops for ornamental, culinary, and medicinal products (Garrett and Buck 1997). Efforts to augment the productivity of commercial non-timber forest products in the Pacific Northwest remain largely undeveloped, with the notable exception of conifer boughs on some industrial and public forests lands (Savage 1995). As demand for naturally-occurring non-timber forest products increases, competition for rights to harvest products (Richards and Creasy 1996) and concerns about viability of populations of commercial species are likely to intensify (Bureau of Land Management Task Force 1993).

Of particular economic interest for the Pacific Northwest is the feasibility of forest management to propagate pine mushrooms (*Tricholoma magnivelare* (Peck) Redhead) in native forests. One chronic obstacle preventing resource development with non-timber forest products such as pine mushrooms, however, is the lack of information about requirements for culturing these products and the effect of producing one resource on production of other resources. The idea of pine mushroom management in North America is recent enough that research results are not available to guide forest managers. Yet, a multi-million dollar export trade in pine mushrooms has developed in the Pacific Northwest during the last twenty years. In some years, 20 percent or more of the pine mushrooms consumed in Japan come from the region ranging from British Columbia to northern California (Weigand 1997d).

Past studies from the region indicate that forestry practices, particularly tree harvesting and burning to promote stand regeneration of desired timber species, are detrimental to productivity of mycorrhizal fungi (Harvey and others 1980a, b). The negative effect of timber harvest neglects the potential role of forest management to culture desired species of fungi by providing appropriate habitat through silvicultural practices. Drawing on research information from Japan and Korea, Weigand (1997b) has suggested that forestry practices can direct stand structures in ways to increase commercial production of pine mushrooms while also enhancing tree growth.

Forest farming entails more complex forest management for multiple objectives. More information and an institutional framework to organize information are required to clarify managerial options about the merits of forest farming. Integrating information in unaccustomed ways from multiple disciplines in social, engineering, and natural sciences is essential. Efforts to expand forest practices to include management of forest products from a commercialized understory requires a synthesis of information and an understanding of risks involved with changing management or with continuing traditional management.

In this paper, we use the Diamond Lake pine mushroom management area to discuss policy issues important to considering forest farming regimes designed to increase pine mushroom production. We first describe the study area, forest products for development, and representative stands from the management area. Three stands are modeled to illustrate managerial and financial aspects of options for developing non-timber resources in high-elevation forests of the southern Cascade Range. Using existing stand inventories, we produce simulation experiments that reveal the probabilities of outcomes and the resulting policy issues if land managers are to undertake concerted pine mushroom management. In addition, we simulate stand development and joint production of timber and non-timber forest products of each stand under five management options to describe financial returns and risks from prospective agroforestry management. Finally, based on results of Monte Carlo simulations, we draw conclusions about the prospects for developing forest farming under different stand conditions, different types of land ownership, and improving predictive power of bioeconomic models of joint production.

6.2. The Study Area

The Diamond Lake pine mushroom management area lies just west of the Cascade Range crest in southern Oregon, USA, at 43°12' 7"N latitude and 122°12' 20"W longitude. Elevation ranges from 1675 to 1750 m. Slopes within the management area range from flat to twenty-three percent. Aspect varies from northwest to east. The management area lies northwest of the Crater Lake caldera, within the heavy ash and pumice deposition zone of volcanic ejecta following the explosion of Mt. Mazama 7,000 years ago (Carlson 1979). In contrast with other Cryand soils in the Cascade Range, soils in the pumice and ash zone are characterized by low available phosphorus, high porosity (Meurisse 1987), little organic matter, and a low percentage of clay compounds by volume (U.S. Department of Agriculture, Soil Inventory database samples S82-OR-019-002 and S91-OR-019-002). Most precipitation falls as snow. Summer rainfall is sparse, usually the result of local thunderstorms. Annual precipitation for the site averages 1525 mm.

The predominant plant association type is *Tsuga mertensiana* (Bong.) Carr / *Vaccinium scoparium* Leib. (Atzet and others 1996), which has one of the lowest basal area stand densities of Pacific Northwest forest types. Five conifer species dominate the overstory at the study site: Pacific silver fir (*Abies amabilis* Dougl. ex Forbes), Shasta red fir (*A. magnifica* A. Murr. var. *shastensis* Lemmon), lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *murryana* Engelm.), western white pine (*P. monticola* Dougl. ex D. Don), and mountain hemlock (*T. mertensiana*). At lower elevations within the management site, Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and white fir (*Abies concolor* (Gord. et Glend.) Lindl.) occur sparsely. Of the major species, *A. amabilis* and *P. monticola* do not appear to form mycorrhizae with pine mushrooms in the management area. Stands within the study site naturally have uneven-aged stand structure except for even-aged patches of lodgepole pine, occurring in disturbed or moist, frost-prone areas. Shrub, forb, and grass species diversity is low as is the percent cover of non-arborescent understory vegetation. Prominent non-tree species in the understory and in gaps include *Arctostaphylos nevadensis* Gray, *Castanopsis chrysophylla* (Dougl.) A. DC var. *minor* (Benth.) A. DC., *Ceanothus prostratus* Benth., *Chimaphila umbellata* (L.) Bart., *C. menziesii* (R. Br. ex D. Don) Spreng, and *V. scoparium*. Fungi species have not been inventoried.

6.3. MUSHROOM: Model Description

This study applies a computer model MUSHROOM (Weigand 1997c) to describe consequences of changing forest management with timber preeminent to joint production of multiple products, including timber. Major non-timber products in the model are pine mushrooms, decorative conifer boughs, pine cones, and Christmas trees. The latter three products are lumped under the rubric "conifer non-timber products." The model estimates yields and values of multiple forest goods from proposed forestry farming systems in high-elevation forests in southern Cascade Range. Parts of the model simulating tree growth adapt and simplify algorithms from the West Cascade variant of the Forest Vegetation Simulator (Johnson 1992, Donnelly 1995 - hereafter FVS), the successor model to PROGNOSIS (Wykoff and others 1982, Wykoff 1986). Equations for tree growth in MUSHROOM are identical to those in FVS except in the case of mountain hemlock. A tree height growth equation developed specifically for the *T. mertensiana / V. scoparium* plant association (Means and others 1986 ms. draft) is used instead.

Features in MUSHROOM not found in FVS include calculations for leaf and stem area indices, crown foliar mass, and cone production. Natural regeneration is based on cone production, disturbance history, existing gap space, and seedling mortality rates. Subprograms also project weather, canopy interception of light and precipitation, and heat and water transfer in the soil. Table 6.1. lists the major subprograms, their function, stochastic variables, and sources of information upon which submodels are based. Information on key input variables and output variables are given in tables 6.2. and 6.3. respectively.

6.4. Experimental Design

In this section we describe scenarios of pine mushroom production functions used in experimental simulations. Responses by pine mushroom colonies in the Pacific Northwest to silvicultural management are poorly known. Only a few records of production have been published or made available to the public (Hosford and others in press, Howard 1995[1]).

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[1] Graham Howard, 1995, report to the district ranger, on file at the Happy Camp Ranger District, Happy Camp, CA.

Table 6.1. An overview of subprograms in the stand-level model MUSHROOM for joint goods production.

Subprograms	*Function*	*Stochastic Variables*	*Major Sources*
AGES	estimate age of trees at breast height	none	Donnelly (1995), Wykoff (1986)
BOUGHS	determine timing of prunings and amount of bough harvests	bough prices	Savage (1995), Schlosser and Blatner (1996)
CHRISTMASTREES	determine feasibility and quantities for Christmas tree harvests	none	USDA Forest Service, Region 6 1996 Cut and Sold Timber Report
CONECROPS	calculate numbers of cone-bearing trees, cones, and seed per hectare; simulate natural regeneration in stand gaps; determine feasibility and quantities of cone crops	cones per tree germination rate rate of seed herbivory seedling mortality rate seeds per cone small tree cover	Franklin and others (1974), Koch (1987), Lotan and Critchfield (1990), Thomas and Schumann (1993), Young and Young (1992)
CROWNRATIOS	calculate changes in live crown ratios of trees	none	Donnelly (1995)
CULTURE	model effects of forest management on stands	mortality rate of planted trees	Weigand (1997c)
DEATH	calculate density-dependent mortality	none	Donnelly (1995)
LEAFLITTER	model accumulation and decomposition of leaf litter on the forest floor;	none	Cromack and others (1991), Edmonds (1980, 1984), Edmonds and Erickson (1994), Edmonds and Thomas (1995), Fogel and Cromack (1977), Stohlgren (1988), Taylor and others (1991), Yavitt and Fahey (1986)
LEAVES	calculate leaf area index , foliage drop, foliar weight and crown volume	none	Sampson and Smith (1993)

Table 6.1. continued.

MUSHROOMYIELD	forecast yields and prices of pine mushrooms	¥ / U.S.$ exchange rate mushroom yield shipping cost total PNW production	Office of the President (1996) Moore and Amaranthus (1997 pers. comm.) Meyer Resources, Inc. (1995) Japan Tariff Association (1976-1995)
NETPRESENTVALUE	calculate the values and quantities of forest products; calculate net present values of products at four discount rates	none	
STUMPAGEPRICING	calculate market stumpage prices	hem-fir chip price sale administration cost stand restoration cost log transport cost	Diamond Lake RD timber sale appraisal data 1971-91
TREEGROWTH	calculate annual tree diameter and height increments	diameter growth height growth	Wykoff (1986), Donnelly (1995)
VOLUMECALC	calculate merchantable timber volume	none	Czaplewski and others (1989), Fahey and others (1986), Harmon and others (1996), Lowell and Cahill (1996), Snellgrove and Cahill (1980)
WEATHERDATA	simulate effects of solar energy and precipitation on soil temperature and moisture	site access for bough and Christmas tree harvests	U.S. Weather Service data for Lemolo Lake, OR
WOODSJOBS	calculate employment from stand management and harvests	none	

Table 6.2. Principal input variables for determining production of goods and their value from the Diamond Lake pine mushroom management area.

Variables	*Functions*
autumn snow pack	determine accessibility to stands during commercial seasons for Christmas trees and decorative conifer boughs
commercial bough prices	calculate market prices for decorative bough crops
cone prices	calculate the value of cone harvests
crown ratio and tree height	determine which trees are suitable for pruning
discount rate	calculate the net present value of forest products
foliar biomass	calculate weight of commercial bough crops
gap space	calculate the composition of tree regeneration in a year
Japan per capita income **and** pine mushroom production in the Pacific Northwest	calculate price for pine mushroom imports to Japan from North America
merchantable wood biomass	calculate the timber harvest volume from a given year
number of cones per tree; **and** number and species of cone-bearing trees	calculate the availability of decorative pine cone crops and calculate the composition of tree regeneration in a year
small tree populations	count trees available for Christmas tree harvests
stumpage prices	calculate the value of timber harvests

plus variables set in the subprogram CULTURE to determine the timing of timber cuts and to manage compositions of tree plantings and numbers of trees in diameter classes.

All production functions are conjectural because data sets for time series relating pine mushroom production to stand conditions at Diamond Lake do not exist. Using management scenarios tied to specific stands and relating scenarios for external market developments, we first generate a sensitivity analysis with Monte Carlo simulations. The second simulation experiment projects statistical distributions for joint outputs of timber and non-timber forest products under different proposed regimes designed to culture pine mushroom colonies and increase their commercial production.

6.4.1. Sensitivity Analysis

The sensitivity analysis assumes five scenarios of pine mushroom production at Diamond Lake in response to forest management. Production volumes and incomes from pine mushrooms under each scenario are projected for stands over a 25-year planning period. Economic variables, independent of hypothesized biological responses of mushroom production to stand management, also affect the valuation of pine mushroom harvests. The economic variables include discount rates, scenarios of Japanese economic growth, and versions of future production capacity of pine mushrooms in the Pacific Northwest region.

6.4.1.1. Pine Mushroom Production Functions at the Stand Level

Table 6.3. defines production response scenarios to management for pine mushrooms and lists production values of commercial pine mushrooms in kilograms per hectare. Time series of per hectare harvest yield data for pine mushrooms are not yet available from Diamond Lake. To simulate productivity at Diamond Lake, the five-year record of average per hectare yield data from Cave Junction, OR, located 160 km to the southwest of Diamond Lake at an elevation of 390 m, is extrapolated to create a Diamond Lake "baseline" production scenario for unmanaged, uneven-aged stands.

Table 6.3. Scenarios for pine mushroom production at the Diamond Lake pine mushroom management area.

	1992	1993	1994	1995	1996
	----------	----------	*kg ha*$^{-1}$	----------	----------
Cave Junction, OR, data					
	9.19	2.06	0.02	2.15	2.22
Chemult, OR, data for comparison					
	--	--	--	2.01	0.52
Scenario 1 - extrapolated "baseline" harvest quantities for Diamond Lake, OR, equal to half the historical production at Cave Junction, 1992-1996					
all years	4.60	1.03	0.01	1.08	1.11
Scenario 2 - slow positive response to pine mushroom management					
years 1 through 5	4.60	1.03	0.01	1.08	1.11
after year 5	9.19	2.06	0.02	2.15	2.22
Scenario 3 - rapid positive response to pine mushroom management					
years 1 through 5	9.19	2.06	0.02	2.15	2.22
after year 5	22.98	5.16	0.04	5.38	5.55
Scenario 4 - no response to pine mushroom management					
all years	4.60	1.03	0.01	1.08	1.11
Scenario 5 - catastrophic response to pine mushroom management or to timber clearcutting					
all years	0.00	0.00	0.00	0.00	0.00

Lower elevation sites have longer fruiting seasons and generally have higher annual production. The Oregon Dunes National Recreation Area at sea level annually produces the largest quantities known per unit area of North American pine mushrooms. Because the effect of increasing elevation on reducing production of North American pine mushrooms is not described, production functions are deterministic in MUSHROOM with fixed values. Data from Cave Junction from 1992 to 1996 (A. Moore and M. Amaranthus, 1997 pers. comm.[2]) are halved to simulate reduced production resulting from the shorter mushroom fruiting season at higher elevations such as at Diamond Lake. Values for average pine mushrooms harvests per hectare from Chemult, OR,[3] for 1995-1996, east of the Cascade Crest, 35 km distant from Diamond Lake, are given as a comparison. In any one scenario, each of the five simulated annual production values has an equal probability of being selected as an harvest amount for any one year during the 25-year planning period.

6.4.1.2. Variables External to Stand Conditions and Affecting Valuation of Pine Mushrooms

Key to understanding the efficacy of stand management for pine mushrooms are two variables external to stand conditions and management. Weigand (1997d) developed a regression with the total harvest quantity of North American pine mushrooms and per capita income in Japan as independent variables and the price per kilogram offered in Japan for pine mushrooms from the U.S. and Canadian Pacific Northwest as a dependent variable. Two scenarios for Japan per capita income are provided: (1) the Japan gross domestic product stagnates (zero economic growth) and per capita income declines or (2) the Japan gross domestic product increases at a constant 1.5 percent annual growth rate

[2]Personal communications, January 1997, Andrew Moore, , pine mushroom picker, Cave Junction, OR, and Michael Amaranthus, biological scientist, Grants Pass, OR.

[3]Personal communication, Gerald Smith, 1997, forester, Chemult Ranger District, Chemult, OR.

for the period 1996 to 2020 and per capita income increases slightly. The former is a worst-case scenario that reduces demand for foreign imports; the latter reflects the average annual economic growth rate in Japan during the recession years 1992-1995 (Japan Government Economic Planning Agency 1996). Both scenarios assume that future Japanese economic growth will not repeat the strong growth seen between 1971 and 1992.

The second external variable relates to production capacity of pine mushrooms in the Pacific Northwest region. Production capacity is treated as the quantity of pine mushrooms offered for export sale to Japan. Two scenarios are assumed: (1) the regional production capacity for the years 1996 to 2020 repeats the regional production values of pine mushrooms in the period 1986-1995; and (2) production capacity for pine mushrooms during 1996 to 2020 doubles annual production recorded from 1986 to 1995. The latter assumes that the number of mushroom pickers increases and concerted forest management for pine mushrooms increase regional production capacity. An increase in Pacific Northwest production means that average prices for North American pine mushrooms would drop, if all economic variables such as production quantities from other pine mushroom producing countries and Japanese per capita income were to remain constant.

6.4.1.3. Discount Rates

Outputs for use in a policy analysis were net present values of goods jointly produced during the 25-year planning horizon. Three different annual discount rates are considered: zero, four-percent, and ten-percent. The first discount rate shows no preference for the timing of benefits accruing from production of goods from the modeled stands. This rate would imply that a land manager desires an even or "sustainable" production of goods over time. A four-percent discount rate is commonly used by

Federal land management agencies to determine feasibility of forest management projects. Ten-percent discounting simulates time preferences of corporate private forest landowners for benefits accruing in the near future. In the last case, both expenses incurred and product yields soon after management commences are weighted more heavily than costs and benefits later in the planning period.

6.4.2. The Stand Modeling Experiment

6.4.2.1. Modeled Stands

Each of three inventoried stands from the Diamond Lake pine mushroom management area were modeled. All three stands had been inventoried at different times. Therefore, all stands were modeled for the number of years from the date of inventory to the baseline year 1995 with the West Cascades variant of the Forest Vegetation Simulator (Donnelly 1995) to provide a common start time for modeling. Comparable data from each stand are presented in table 6.4. Fungal infections and parasitic infestations of mistletoe (*Arceuthobium* spp.) are naturally widespread in unmanaged stands. Drought stress is also evident in stand 357 which has a very large number of small Pacific silver fir trees. Slow growth, drought conditions, and tree diseases undermine commercial development of merchantable timber volume.

6.4.2.2. Silvicultural Prescriptions

Knowledge about silvicultural practices to promote increased production of pine mushrooms in native forests in the Pacific Northwest is fragmentary. To increase understanding about practices promoting commercial crops of pine mushrooms, management experiments have been designed to test assumptions about pine mushroom

Table 6.4. Stand data from stands with management experiments at the Diamond Lake pine mushroom management area.

Stand Feature	Stand 355	Stand 357	Stand 401
Elevation (m)	1 735	1 705	1 675
Aspect	NW to NE	NW to NE	W to NE
Slope (percent)	5	10 - 23	15
Position	ridge	mid- to bottom-slope	upper slope
Western white pine			
100-yr site index (m)	29	30	23
Basal Area (m^2 ha^{-1})	24.6	53.4	60.1
Major overstory species	MH	SF, MH	SF
Minor overstory species	RF, WP	LP, WP	LP, WP
Understory species	all 5 species	SF (MH)	SF, LP
Fungal Infection	WP, LP	WP, LP	WP, LP, RF
Mistletoe Infestation	SF, MH	SF, MH	--
Drought Stress	--	SF, MH	RF
Timber Quality	poor	poor	poor

LP = lodgepole pine MH = mountain hemlock RF = Shasta red fir SF = Pacific silver fir WP = western white pine

production (Pilz and others 1996, Weigand 1997c). For this analysis, management prescriptions designed for the Diamond Lake pine mushroom management area are used to simulate possible results. An outline of silvicultural treatments for each simulation for each of the three stands is presented in table 6.5. Complete details of silvicultural prescriptions over the 25-year planning period is given in Weigand (1997c). Silvicultural

Table 6.5. Outline of stand-specific silvicultural treatments designed to augment production of North American pine mushrooms at the Diamond Lake pine mushroom management area.

Stand 355	
Control 1	No investment in management and maximum conservation of stand structure and composition. Pine mushrooms and pine cones may be harvested under the assumption that harvesting these products does not alter the stand.
Control 2	No investment in management and maximum resource extraction in year 0. Pine cones and Christmas trees may be harvested in subsequent years. Pine mushrooms are assumed to disappear as an available resource after clearcutting. As costs of intensive pruning outweigh market value of boughs, no pruning or commercial bough harvesting occurs.
Prescription 1	Retain a minimum of 30 tph of old-growth Shasta red firs until year 25, 25 tph thereafter . Regenerate mountain hemlock and Shasta red fir naturally in the understory.
Prescription 2	Retain a minimum of 15 tph each of old-growth Shasta red firs and mountain hemlocks until year 25, 13 tph of each species thereafter. Regenerate Shasta red firs naturally in the understory.
Prescription 3	Retain a minimum of 30 tph of old-growth mountain hemlocks until year 25, 25 tph thereafter. Regenerate Shasta red fir naturally in understory.
Stand 357	
Control 1	As for stand 355 except that pine mushrooms are not available in this young stand.
Control 2	As for stand 355.
Prescription 1	Retain 315 tph Pacific silver fir for potential Christmas tree crops. Regenerate with mountain hemlock seed trees, then remove seed trees.
Prescription 2	Retain 25 tph Pacific silver fir to maintain tree species diversity. Regenerate with mountain hemlock seed trees, then remove seed trees.
Prescription 3	Retain 25 tph each of Pacific silver fir and mountain hemlock to maintain tree species diversity. Regenerate understory with lodgepole pine seed trees, then remove seed trees.

Table 6.5. Continued.

Stand 401	
Control 1	As for stand 355.
Control 2	As for stand 355.
Prescription 1	Retain 60 tph of old-growth Shasta red firs until year 25, retain 25 tph thereafter.
	Regenerate Shasta red firs from old-growth trees and with 60 tph of Shasta red firs as seed trees with dbh's between 18 and 50 cm, then remove seed trees.
Prescription 2	Retain 60 tph of old-growth Shasta red firs until year 25, retain 25 tph thereafter.
	Regenerate using old-growth trees and lodgepole pines with 60 tph of lodgepole pines with dbh's greater than 10 cm, then remove seed trees.
Prescription 3	Retain 30 tph of old-growth Shasta red firs, until year 25, retain 25 tph thereafter.
	Regenerate using old-growth trees plus seed trees consisting of 30 tph of Shasta red firs with dbh's between 18 and 50 cm and 30 tph of lodgepole pines with dbh's greater than 10 cm; then remove seed trees.

Note: All prescriptions except controls call for planting rust-resistant western white pine seedlings.

prescriptions modeled here are also designed to improve tree growth rates, reduce the spread of fungal diseases and plant parasites, boost the population of rust-resistant western white pine trees, and increase incomes from non-timber forest products.

6.4.2.3. Other Non-Timber Conifer Products

Non-timber products derived from conifer species are considered here as supplemental sources of income in stands managed for pine mushrooms. Production functions for Christmas trees, decorative boughs, and pine cones are simulated in detail because their outputs can be directly linked to output data from the tree growth model. Table 6.6. summarizes constraints on the yields of these products and of pine mushrooms.

Table 6.6. Production constraints for non-timber products.

pine mushrooms

- harvesters do not collect pine mushrooms in the years when timber is harvested to avoid logistical hazards of overlapping product harvests in the autumn;
- in high elevation stands, commercial pine mushrooms do not occur until 25 to 30 years after clearcutting; and
- no commercial production occurs in stands dominated by trees species that do not host pine mushroom colonies (for example, stand 357 initially dominated by Pacific silver fir);

decorative conifer boughs

- trees are pruned to 1.2 m, 2.4 m, and 5.3 m if tree heights exceed 2.4 m, 4.8 m, and 13.5 m respectively;
- net conifer bough value must equal \$800 ha^{-1} or commercial mass must exceed one metric tonne ha-; but
- boughs are harvested when more than 250 pine trees ha^{-1} require pruning to prevent infection by blister rust and gall rust fungi;
- only Shasta red fir and western white pine boughs are marketable in all years;
- Pacific silver fir is marketable only if trees are open-grown;
- boughs from lodgepole pine and mountain hemlock are marketable in half of all years;
- after 2010, half of all years have species-specific bough prices 25 percent higher than the base price for the species in that year.

Christmas trees

- a minimum of 125 trees ha^{-1} must be available for harvest in a given year;
- Shasta red fir and open-grown Pacific silver fir are the only marketable species;
- trees may not be previously pruned;
- trees must be between 1.5 and 3.0 m tall with a crown length at least 1.25 m.

decorative cones

- lodgepole pine and western white pine are the only marketable species;
- minimum threshold crop value for commercial harvest is \$500.00 ha^{-1}.

6.4.2.4. Stumpage Prices

Future stumpage prices modeled here rely on a partially stochastic model developed by Weigand (1997a). Deterministic prices for lumber by species and lumber grade depend on their historical correlation to annual averages of regional prices for all lumber as recorded by the Western Wood Products Association, Portland, OR, between 1971 and 1995 and on future projections of annual average prices of lumber from the Timber Assessment Market Model (Adams and Haynes 1996) used by the U.S. Forest Service reports to Congress in accordance to the Resource Protection Act of 1980. Future stumpage prices in a given year for a particular lumber grade from a given tree species are calculated by deducting stochastically determined manufacturing and stump-to-mill costs from the deterministic future lumber prices. Statistical distributions of wood processing costs are derived from appraisal data, expressed in constant 1990 dollars, for timber sales in the Diamond Lake Ranger District from 1971 to 1991.

Stumpage prices provide a convenient means by which to judge eventual opportunity costs foregone if management of high-elevation stands in the southern Cascade Range switches to emphasize joint production with non-timber forest products. While public acceptance of clear cutting at high elevations may be low, modeling financial returns for clear cutting serves as a financial baseline against which other management options might be evaluated.

6.5. Results

Table 6.7. explains the variable contents of the simulations depicted in figure 6.1. Figure 6.1. graphs the empirical cumulative distribution functions of Monte Carlo simulations of financial returns from pine mushrooms over the 25-year planning period. Each graph in figure 6.1. displays the 1,000 simulated totals of the 25-year value of pine mushroom

Table 6.7. Runs listed in figure 6.1. and explanations of their run numbers.

Run number in figure 6.1.	*GDP growth rate in Japan*	*Pacific Northwest regional production*	*Stand production at Diamond Lake*
R101111	0%	1 x past decade	Baseline / No management response
R101121	0%	2 x past decade	Baseline / No management response
R101211	1.5%	1 x past decade	Baseline / No management response
R101221	1.5%	2 x past decade	Baseline / No management response
R121113	0%	1 x past decade	2 x Baseline after 5 years
R121123	0%	2 x past decade	2 x Baseline after 5 years
R121213	1.5%	1 x past decade	2 x Baseline after 5 years
R121223	1.5%	2 x past decade	2 x Baseline after 5 years
R121114	0%	1 x past decade	5 x Baseline after 5 years
R121124	0%	2 x past decade	5 x Baseline after 5 years
R121214	1.5%	1 x past decade	5 x Baseline after 5 years
R121224	1.5%	2 x past decade	5 x Baseline after 5 years

crops, expressed in 1990 U.S. dollars on the x-axis. The paired y-coordinate is the probability of the actual total 25-year value of pine mushroom crops being less than or equal to the corresponding value on the x-axis (Conover 1980). The y-axis units are probability quantiles marked at 0.2 intervals. Differences in the shapes of distribution function curves indicate visually relative measures of difference among curves.

All simulations (n=1,000 in all cases) show comparatively greater economic return when the pine mushroom production scenario is increased from baseline production (those runs suffixed with the number "1" as in figure 6.1a) to an eventual two-fold (runs suffixed with the number "3") or a five-fold (runs suffixed with the number "4") increase in pine

Figure 6.1.: Sensitivity analysis for financial returns from pine mushroom cultivation.

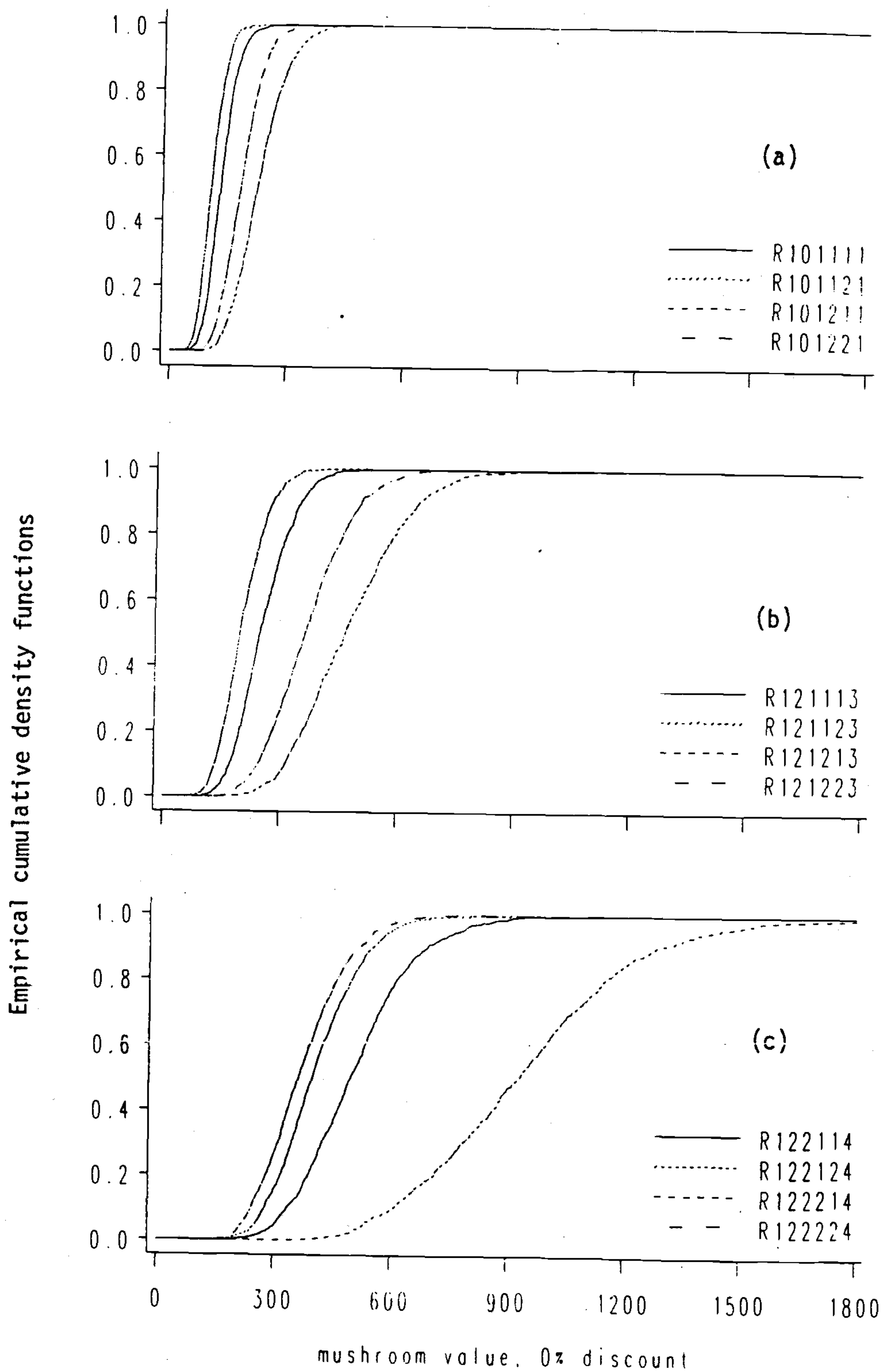


Figure 6.1. Continued.

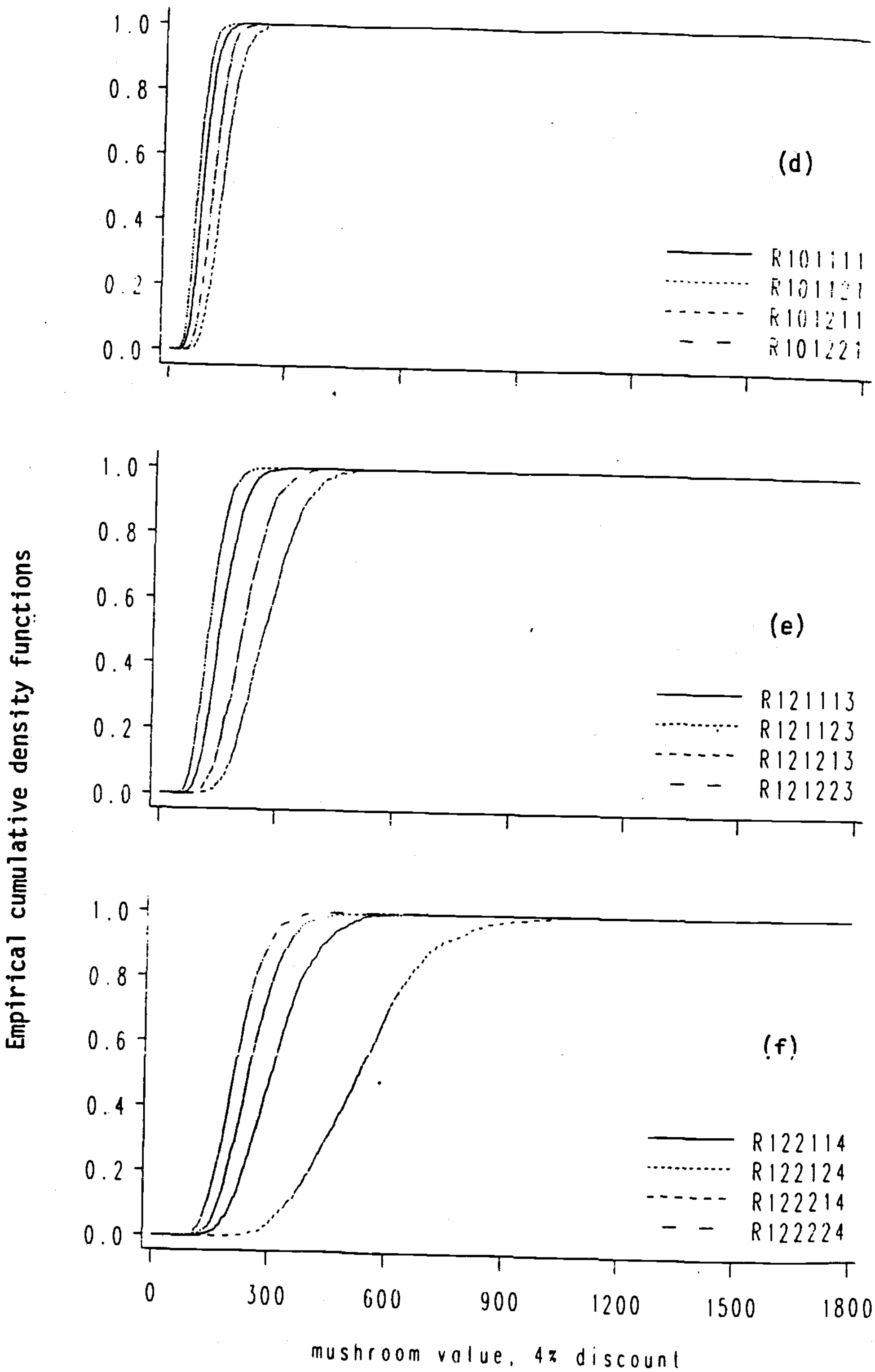
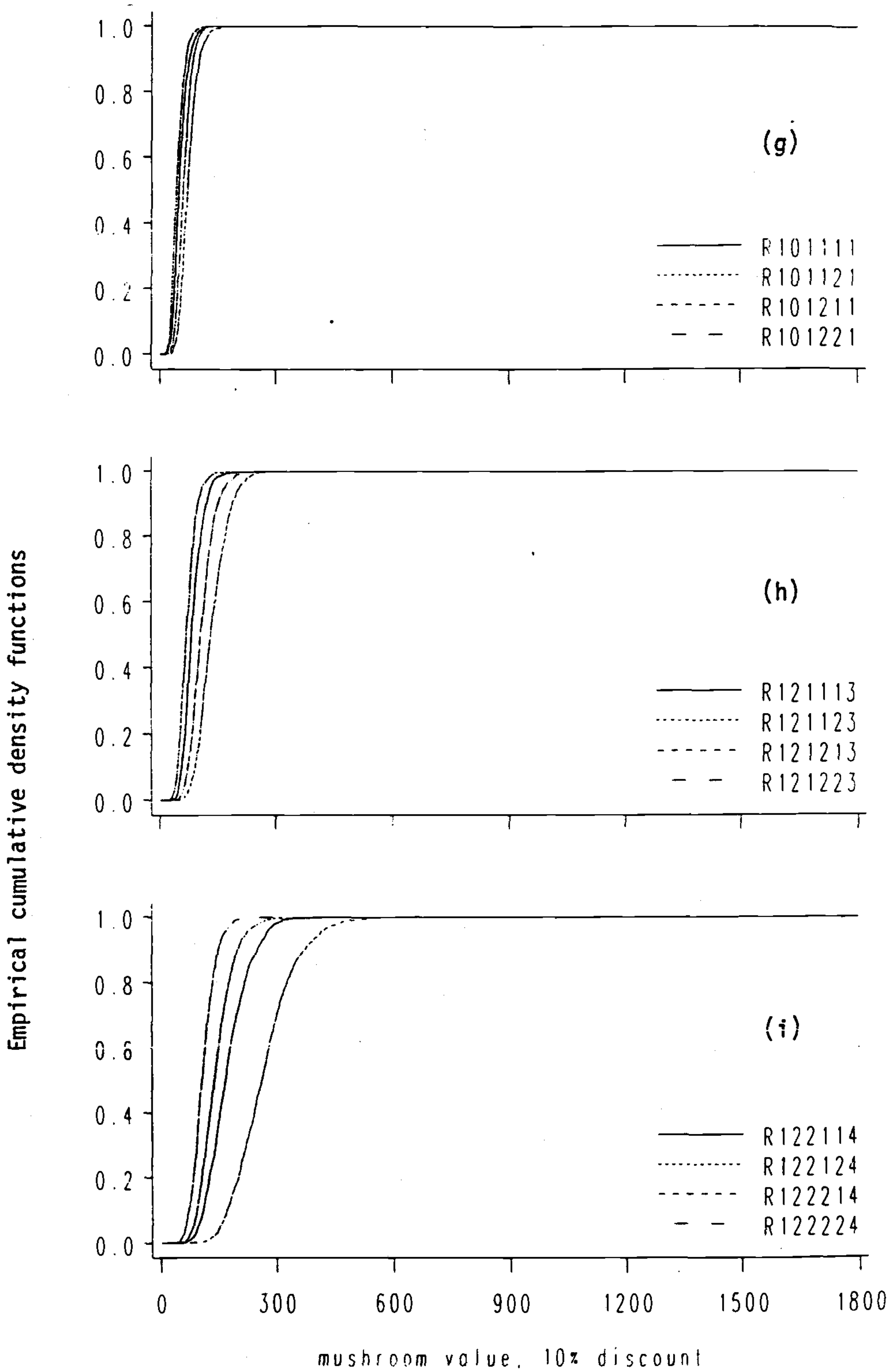


Figure 6.1. Continued.



mushroom production. Increases in productivity magnify differences among the different scenarios for regional Pacific Northwest production and Japanese gross domestic product. Low biological ("baseline") production viewed with high (e.g. 10%) discount rates indicate that landowners with greater interest in short-term profits are essentially indifferent to pine mushrooms regardless of market developments (figure 6.1g.). Prospects of five-fold increases over baseline production, however, are disproportionately more attractive to land managers under all discount rates examined if the following two future trends external to stand management hold true: the Japanese per capita income continues to grow at a modest real gain of 1.5 percent annually and the total production of pine mushrooms from the Pacific Northwest, including British Columbia, remains at levels recorded during 1986-1995. Therefore, innovators with a long-term view toward income generation on their lands will be most likely to invest in pine mushroom agroforestry.

If these two conditions do not come about, the prospects for investment are less attractive. If pine mushroom exports to Japan were to double from North America at the same time as stand-level production quintuples, the returns to forest land managers will be more similar to value obtained under zero economic growth in Japan (figure 6.1c.). The increased financial returns from the modest best-case scenario here show that even with the ten percent discount, returns are significantly better. In general, if the Pacific Northwest produces pine mushrooms at quantities seen during the past decade and modest economic gains continue in Japan, the first landowners to start cultivating pine mushroom production will see the largest gains in profits. Once enough suppliers enter the market to significantly increase the regional production, unit prices of mushrooms will drop but harvest overall will still yield greater value than no management. The worst scenario for a landowner will be investment in pine mushroom culture in the event that the Japanese economy stagnates in coming years.

Timber harvests in year zero of each simulation provide income for future stand management. Table 6.8. gives stumpage prices for timber harvested in year zero for each of the three silviculture treatments for each stand plus the control scenario options of no management and maximal clear cutting.

Table 6.8. Stumpage value of timber cut in year zero (1995) for three stands from the Diamond Lake pine mushroom management area.

	Clearcut Scenario	Scenario #1	Scenario #2	Scenario #3	No Management Scenario
	--------------------constant 1990 U.S. dollars per hectare-------------------				
Stand 355					
	342	189	189	190	0
	(55)	(28)	(28)	(28)	--
Stand 357					
	2109	2097	1281	1945	0
	(217)	(221)	(121)	(216)	--
Stand 401					
	7884	1970	3028	3166	0
	(617)	(172)	(256)	(254)	--

Figures represent averages and (in parentheses) standard deviations for n=1000 simulations.

The income realized at year zero represents potential income available for reinvestment into stand management for joint production of pine mushroom and timber. Projections of averages and standard deviations for the value of harvests for jointly produced goods during the 25-year planning cycle are given for each stand, each stand scenario, and three discount rates in tables 6.9. through 6.11.

Timber outputs during the 25-year period are high for prescriptions in stands 357 and 401, with income resulting mostly from seed tree harvests five years after the initial silvicultural intervention. Most timber harvest income at the end of the period is small in stands 355 and 357, but quite large for several of the management scenarios for stand 401.

Appendices to this chapter contain graphs of cumulative distribution functions, arranged by stand, for all individual product values and for net present values of the different scenarios. A land manager can see the "spread" or relative variability of estimates for particular financial outcomes. Financial performances of resource production can inform about the contribution of each resource to stand incomes and the risks associated if expected production of pine mushrooms differs from expectation. Of particular importance is the financial performance of agroforestry systems in the event of a failure to improve pine mushroom production through investments in management.

The following paragraphs summarize results of simulated outputs for each stand under the management scenario regimes and are based on the data reproduced in the appendices for the respective stand.

6.5.1. Stand 355

Tree basal area per hectare before management is low, about half the basal area of the other stands examined here (table 6.4). Conditions reflect high-graded stands after earlier timber harvests. Timber volume and value available for harvest in year zero are correspondingly small. Each management scenario for pine mushrooms yields nearly identical small amounts of timber income in year zero. Creating the desired number of large trees for anchoring pine mushroom colonies and crop trees will take time because of

Table 6.9. Projected net present values of goods produced from stand 355, Diamond Lake pine mushroom management area, 1996-2020.

	0% discount				4% discount				10% discount			
	Timber	Non-Timber Conifer Products	Pine Mushrooms	**Total**	Timber	Non-Timber Conifer Products	Pine Mushrooms	**Total**	Timber	Non-Timber Conifer Products	Pine Mushrooms	**Total**
	constant 1990 U.S. dollars per hectare											
Control 1	0	0	225	**225**	0	0	134	**134**	0	0	73	**73**
	--	--	(59)	(59)	--	--	(35)	(35)	--	--	(21)	(21)
Control 2	0	27	0	**27**	0	15	0	**15**	0	6	0	**6**
	--	(75)	--	(75)	--	(40)	--	(40)	--	(16)	--	(16)
Scenario 1	756	-2023	481	**-786**	284	-920	278	**-358**	70	-319	141	**-101**
	(208)	(499)	(131)	(557)	(78)	(219)	(73)	(244)	(19)	(75)	(39)	(86)
Scenario 2	338	-828	479	**-11**	126	-416	276	**-13**	127	-161	140	**11**
	(128)	(696)	(134)	(711)	(48)	(293)	(74)	(302)	(48)	(90)	(39)	(97)
Scenario 3	0	-1979	500	**-1479**	0	-899	282	**-617**	0	-312	140	**-171**
	--	(487)	(136)	(512)	--	(213)	(75)	(289)	--	(73)	(39)	(84)

Table 6.10. Projected net present values of goods produced from stand 357, Diamond Lake pine mushroom management area, 1996-2020.

	0% discount				4% discount				10% discount			
	Timber	Non-Timber Conifer Products	Pine Mushrooms	**Total**	Timber	Non-Timber Conifer Products	Pine Mushrooms	**Total**	Timber	Non-Timber Conifer Products	Pine Mushrooms	**Total**
	constant 1990 U.S. dollars per hectare											
Control 1	0 --	0 --	0 --	**0** --	0 --	0 --	0 --	**0** --	0 --	0 --	0 --	**0** --
Control 2	0 --	0 --	0 --	**0** --	0 --	0 --	0 --	**0** --	0 --	0 --	0 --	**0** --
Scenario 1	0 --	44 (236)	0 --	**44** (236)	0 --	17 (101)	0 --	**17** (101)	0 --	4 (31)	0 --	**4** (31)
Scenario 2	2565 (336)	220 (516)	0 --	**2785** (629)	2108 (276)	87 (205)	0 --	**2195** (352)	1592 (209)	24 (59)	0 --	**1616** (352)
Scenario 3	420 (31)	51 (241)	0 --	**471** (243)	345 (26)	20 (103)	0 --	**366** (106)	261 (20)	5 (31)	0 --	**266** (37)

Table 6.11. Projected net present values of goods produced from stand 401, Diamond Lake pine mushroom management area, 1996-2020.

	0% discount				4% discount				10% discount			
	Timber	Non-Timber Conifer Products	Pine Mushrooms	**Total**	Timber	Non-Timber Conifer Products	Pine Mushrooms	**Total**	Timber	Non-Timber Conifer Products	Pine Mushrooms	**Total**
	---constant 1990 U.S. dollars per hectare---											
Control 1	0	0	228	**228**	0	0	136	**136**	0	0	74	**74**
	--	--	(62)	(62)	--	--	(36)	(36)	--	0	(22)	(22)
Control 2	0	241	0	**241**	0	199	0	**199**	0	158	0	**158**
	--	(105)	-	(105)	--	(73)	--	(73)	--	(58)	--	(57)
Scenario 1	11 415	-1311	467	**10 572**	9382	-769	267	**8880**	7088	-365	134	**6857**
	(172)	(86)	(140)	(750)	(632)	(83)	(77)	(644)	(478)	(66)	(40)	(485)
Scenario 2	589	0	472	**1060**	484	0	270	**754**	365	0	136	**501**
	(35)	--	(137)	(142)	(29)	--	(76)	(82)	(22)	--	(40)	(45)
Scenario 3	8491	-1368	471	**7594**	6979	-785	270	**6464**	5272	-361	136	**5046**
	(568)	(86)	(138)	(592)	(467)	(76)	(76)	(479)	(353)	(70)	(39)	(361)

the initial low stand density. Additional subsidies may be needed when cone crops and pine mushrooms cannot offset expenses incurred from bough pruning.

Creating a stand structure with features designed to enhance tree growth and pine mushroom productivity is costly in stand 355. The cost is expressed mostly in the net value of bough harvests averaging undiscounted \$1,500 to 2,500 ha^{-1} (\$250 to 350 ha^{-1} at a ten percent discount) during the planning period. Most bough costs are incurred late in the planning period. By contrast, the slow positive response of pine mushroom crops to management represented in these simulations contributes about \$450 ha^{-1} undiscounted for the entire period. Projected value from production of all other goods does not compensate for the pruning costs for boughs during the first 25 years, except under a ten percent discount rate.

Simulations of scenario two (simulation series R522213) have an approximately 0.4 probability of breaking even financially among the different forest products at a zero discount, or 0.5 probability at ten percent discount (appendix 6.1.). The likelier probability of breaking even under the higher discount rate results from pruning costs incurred proportionately later and weighted less. These results assume the validity of pine mushroom production simulated here.

Income from cone crops in stand 355 is larger, and cone crops, when present, are the most valuable crop from the stand during the simulation period. The cumulative distribution of simulated cone crops shows a probability of greater than 0.5 that there will be cone crop for scenario two. Probabilities estimated from the other alternatives are about 0.25 for cone incomes during the planning period. The steep first step in the function is the result of the minimum threshold value for cone income. Steps within the distribution indicate different numbers (up to three) of commercial cone harvests during the planning period for a single simulation.

Christmas trees produce income in less than five percent of simulations of pine mushroom management scenarios. Without specific attention to generating and retaining unpruned natural regeneration of Shasta red fir trees, commercial quantities of Christmas trees are unlikely. Crops of Christmas trees might be more frequent if priority were given to leaving young Shasta red fir trees unpruned until they exceed the size suitable for Christmas trees. In this way, fewer firs would be pruned and less often.

Timber harvests at year 25 reduce overstory trees from about 30 to 25 per hectare. Emphasizing retention of Shasta red firs generates more timber income than options with mountain hemlock at the close of the planning period because the requisite number of mountain hemlock overstory trees is still lacking at the end of 25 years. The value of timber produced from prescription 1 is greater on average because it consists of Shasta red fir only.

Control simulations without management have smaller, less diverse, and thus more predictable ranges of resource outputs during the planning period. Control one (no management + minimum extraction) produces pine mushrooms at the baseline level throughout the 25-year period in all simulations, and about 15 percent of stand simulations for control two (no management + maximum timber extraction) produce a Christmas tree crop. The amount of Christmas trees produced after harvest clearcutting in year zero represents the likely upper limit to improving the probability of harvesting a commercial Christmas tree crop during the planning period, unless special measures are not taken to regenerate Shasta red fir and to exclude other tree species.

6.5.2. Stand 357

Most large trees are removed from the stand to open the way for regenerating tree species that host pine mushroom colonies. Prescriptions one and three approach the timber value produced in the clearcut control scenario, and timber harvest income per hectare exceeds one thousand dollars in all cases for year zero. No pine mushroom income is expected during the first twenty-five years of stand management while stand composition is being converted to host tree species, either lodgepole pine or mountain hemlock. Removing the old, mostly diseased or defect-laden trees is assumed to extirpate any active pine mushroom colonies until after the planning period ends.

Positive net present values for scenarios two and three result from seed tree cuts in the fifth year after management begins. The higher timber value and volume from the seed cut in scenario two (table 6.10.) compensates for the lighter initial cut in year zero (table 6.8.). In contrast to stand 355, bough value is less negative by an order of magnitude. Smaller trees are pruned and costs per tree are lower for these smaller trees. Cones provide income in between ten and 22 percent of simulation runs for scenarios. Christmas tree crops from Pacific silver fir, planned for scenario one, fail to materialize by year 12 of the simulation period. The other scenarios also fail to produce adequate quantities at any time of open-grown Pacific silver fir or Shasta red fir, the species targeted for Christmas tree crops.

The time required to recreate new stands capable of hosting pine mushrooms out of Pacific silver fir stands without pine mushroom production presents an obstacle to generating income in the first cycle of management in essentially even-aged young stands. Conversion to uneven-aged structure will have to wait until subsequent cycles. Benefits of timber harvested in year zero plus any seed tree cuts, however, cover costs of management for the first 25 years. Under the three management scenarios, some income is produced in contrast to the zero values for the two control scenarios.

6.5.3. Stand 401

This stand achieves more successfully the uneven-aged stand structure striven for in conserving pine mushroom colonies in more open stands. One-sixth to one-third of the stand timber value is removed in year zero, with subsequent seed tree removals at year five, and overstory removal again in year 25. Lodgepole pines retained as seed trees in prescription two contribute considerably less to timber income from seed tree cuts because of the lower d.b.h. limit acceptable for lodgepole pine seed trees.

Cone crops whether from western white pine or lodgepole pine fail to materialize. Christmas trees crops develop only under the "no management + maximum extraction" control scenario, but occur with about 0.9 probability. This is further evidence that pruning may incur added costs to stand management and at the same time reduce potential revenue from true firs that could be cropped as Christmas trees. Timber remains the major source of income during the initial planning cycle.

Stand 401 is the most timber-rich stand. In the clearcut scenario, \$7884 is generated from stumpage in year zero per hectare. In the following 25 years, an additional amount averaging \$ 241 is cropped from Christmas trees. Under a ten-percent discount, total stand revenues from a combination of timber and non-timber forest products from the three management scenarios ranges from 0.43 to 1.10 times the income value of the clearcut control. Timber produces most of the value during the 25-year period for each scenario. Simulation results show that foregoing clearcutting and switching to uneven-aged management with joint production of non-timber forest products does not necessarily result in a net loss to stand incomes, even under high discount rates, during the first planning cycle. The most important factor is devising the silvicultural regimes to generate the best combination of timber and non-timber forest products. More difficult is to answer the question how much can non-timber forest products contribute to stand income in the second cycle when overstories are stabilized and timber volumes drop.

Better descriptions of joint production functions, particularly with pine mushrooms, are needed before this question can be answered with certainty.

6.6. Discussion

Different probabilities and quantities of resource production reported here reflect differences in the simulated responses of stands to management alternatives. Some differences result from different initial stand conditions; other differences come from differences in targeted stand composition and product extraction during silvicultural management. Stands represent conditions of previous harvest high-grading (stand 355), stagnant Pacific silver fir understories (stand 357), and mixed-species old-growth mountain hemlock and Shasta red fir (stand 401). Agroforestry systems containing old-growth host trees to culture pine mushroom colonies intensively and interspersed with cohorts of western white pine grown for high-quality timber appear likely to develop at different rates in stands with different initial conditions.

Stand 401 is better suited than stand 355 both economically and silviculturally because more income can be generated from timber to cover costs of investment in pine mushroom management and initial stand density is greater to provide desired overstory canopy composition. Unless a stand is already well-stocked with the appropriately diverse tree age and tree species mix, considerable time may pass before results of increased pine mushroom productivity is realized on high-elevation sites with naturally low productivity. Once, however, environmental conditions favorable to producing pine mushrooms are achieved, stand features will change relatively slowly. Manipulating tree density with Christmas tree harvests or pre-commercial thinning or manipulating leaf area index with commercial bough pruning may yield some income and extend the duration of stand conditions favorable to pine mushrooms between schedules for overstory and mid-story thinnings.

Because uncertainties about stand outcomes and flow of incomes are great, the first 25-year planning cycle requires monitoring and likely requires adjustments to management. Monitoring pine mushroom production is critical to decision-making in future management reviews because no information is yet available about the responses of pine mushrooms to these and other management scenarios. Information gained from responses will guide planning for the next 25-year planning cycle of uneven aged management. The greater the response by pine mushrooms to stand conditions plus market developments for pine mushrooms will determine the extent of intensification or abandonment of pine mushroom cultivation at high elevations.

6.6.1. Alternate Products and Alternative Product Mixes

If pine mushroom crops fail to increase, partial timber harvests compensate by producing income up front at the beginning of the period. The naturally slow aboveground production rate and low biological plant diversity in high-elevation forests on volcanic ash and pumice soils limits the number of feasible economic alternatives to production if pine mushroom fails. Forest farming with *Chimaphila* species may present another opportunity, but problems with seed germination and asexual propagation and poor understanding of the species commercial markets hamper development. In cases where stand management systems with pine mushroom fail to produce desired financial gains, commercial resources such as pine cones may deserve more intensive management. Other stand silvicultural alternatives may forego producing pine mushrooms altogether and concentrate on a narrower range of products. Stands comprised primarily of lodgepole and western white pine, for example, may produce greater income from yields of pine boughs, pine cones, and timber in contrast to the five-product system advanced in the scenarios presented here. MUSHROOM can be used as a tool to test the validity of these alternatives.

6.6.2. Pruning

Pruning programs deserve careful reformulation as a means to increase the quantity or quality of forest products from agroforestry systems designed for pine mushroom production. Comprehensive pruning to reduce leaf area index and improve timber quality proves to be a costly practice in stands targeted for uneven-aged management. As a measure to improve timber quality, pruning manifests benefits only after several decades and beyond the scope of the 25-year period studied here. Discounting future quality premiums for timber against early pruning costs may eliminate any net resource revenue. This question will be important in the second 25-year cycle as the first young western white pine trees are commercially harvested.

Improving pruning techniques and refining pruning programs may reduce early stand costs for pruning and open options for producing other goods. One solution is to prune fewer trees by limiting the tree species to be pruned, specifically to plan bough harvests for tree species such as Shasta red fir and western white pine which have consistent markets for boughs. Reduced frequency of prunings, particularly for true firs, would lower pruning costs. Pruning true firs only after they are 5 m tall, prevents pruning of small true firs that could then be harvested as Christmas trees. The low value of lodgepole pines as crop tree in the stands with uneven-aged management would speak for their retention for biological diversity but not for intensive pruning management for boughs and robust crop trees.

The efficacy of commercial bough management in a joint production agroforestry system is untested. Danish and American management (Bang 1988, Holstener-Jørgensen 1986, Savage 1995, Hinesley and Snelling 1992) for commercial conifer boughs from true firs has emphasized heavy inputs of labor, fertilizers, and pesticides to increase foliage growth and yields in monocultural, even-aged stands. Whether less intensive management with concurrent products can still provide commercial yields is not known because responses to different investments in labor and fertilizer are just beginning to be chronicled (Fight and others, ms. in preparation). Also, resources derived in association with a species may be competitive rather than complementary. Effects of fertilizers to enhance bough foliage of young Shasta red firs may have negative effects on pine mushroom yields from colonies in the same stand. Long-term monitoring of silvicultural practices is required to confirm efficacy of this type of management.

6.6.3. Risk

Montgomery (1996) underscores the need to distinguish between private risk and public risk as well as between long-run and short-run risk. Results from the current simulations suggests that options exist to maintain stand incomes from non-timber forest products when considerable numbers of overstory trees are retained after harvest. A concern for the broader public is that products used to create value at the stand level to compensate for reduced timber revenues may not have sufficient capacity to create additional employment outside the forest. That is to say, the secondary employment generated from processing boughs, cones, Christmas trees, and pine mushrooms may be considerably less than employment generated from timber processing on a product dollar basis. Therefore, although stands may still produce comparable incomes from primary products and keep public forest coffers at near constant levels from jointly produced forest products, the risk of diminishing jobs and wages in the private sector based on forest products remains. No studies have yet to be conducted to determine how well non-timber forest products can contribute to secondary employment in place of timber products.

The temporal scope of this paper is relatively short. Spans usually considered for biological models of forest growth (50 to 500 years typically) are longer and the planning horizon for most Congressional or Forest Service planning is briefer (two to ten years). The short-run risk that investments for pine mushrooms prove fruitless is offset by the compensating income from partial timber cuts in stands which might otherwise not be cut. Cutting is a means to improve future stand tree growth and soil conditions for mushroom fruiting as much as to generate immediate income. Longer-term risk into future 25-year cycles is especially clouded because our information of the joint production functions for the non-timber forest products, and especially pine mushroom, is poorly developed. An important investment to reduce long-term risk is a program of management experiments of the kind simulated here. By incorporating learning into continually honed management practices designed to increase economic production without compromising the productive capacity of forest ecosystems, long-term risks can be characterized and minimized.

6.6.4. Iterative Policy Making

The sets of simulations produced in this study constitute a first round of modeling with MUSHROOM to increase learning. We suggest that a combination of iterative modeling coupled with iteratively refined management experiments provide information for continuous course correction for policy direction in stand management. Choosing the scenario model that produces the best net present value under a relevant discount rate leads to refining the most productive initial program. At the same time, new data regarding production from on-site in an adaptive management experiment lengthens the time-series of available data. Price data are also incorporated. Updating the model is important to fine tune management and allow for new contingencies as new information is made available.

Results from this first round of modeling suggests the following refinements to management:

(1) management for lodgepole pine as a major source for timber and host for pine mushroom colonies is not effective in uneven-aged management when compared to

management alternatives for mountain hemlock or Shasta red fir;
(2) production of commercial boughs and Christmas trees can be compatible resource goals for true firs, but a temporal sequence of cropping Christmas trees before embarking on pruning could offset pruning costs and increase incomes from boughs;
(3) pruning western white pine trees should be considered distinctly from pruning hem-fir species;
(4) in the event that pine mushrooms do not respond to management efforts to increase production, non-timber conifer products, particularly pine cones and Christmas trees may provide additional income not supplied under control management scenarios;
(5) timber harvests in year zero and in subsequent years provide the greatest share of income through the first 25-year planning cycle;
(6) average total undiscounted value of pine mushrooms per hectare over 25 years will contribute on average about $100-200 for a baseline level of production, $150-500 for doubling production from the baseline within five years, and $300-900 for a five-fold increase from the baseline production within five years; and
(7) monitoring for time-series data as part of management experiments provides means for continuous improvement in describing stochastic economic and ecological processes that affect the production and harvest value of pine mushrooms.

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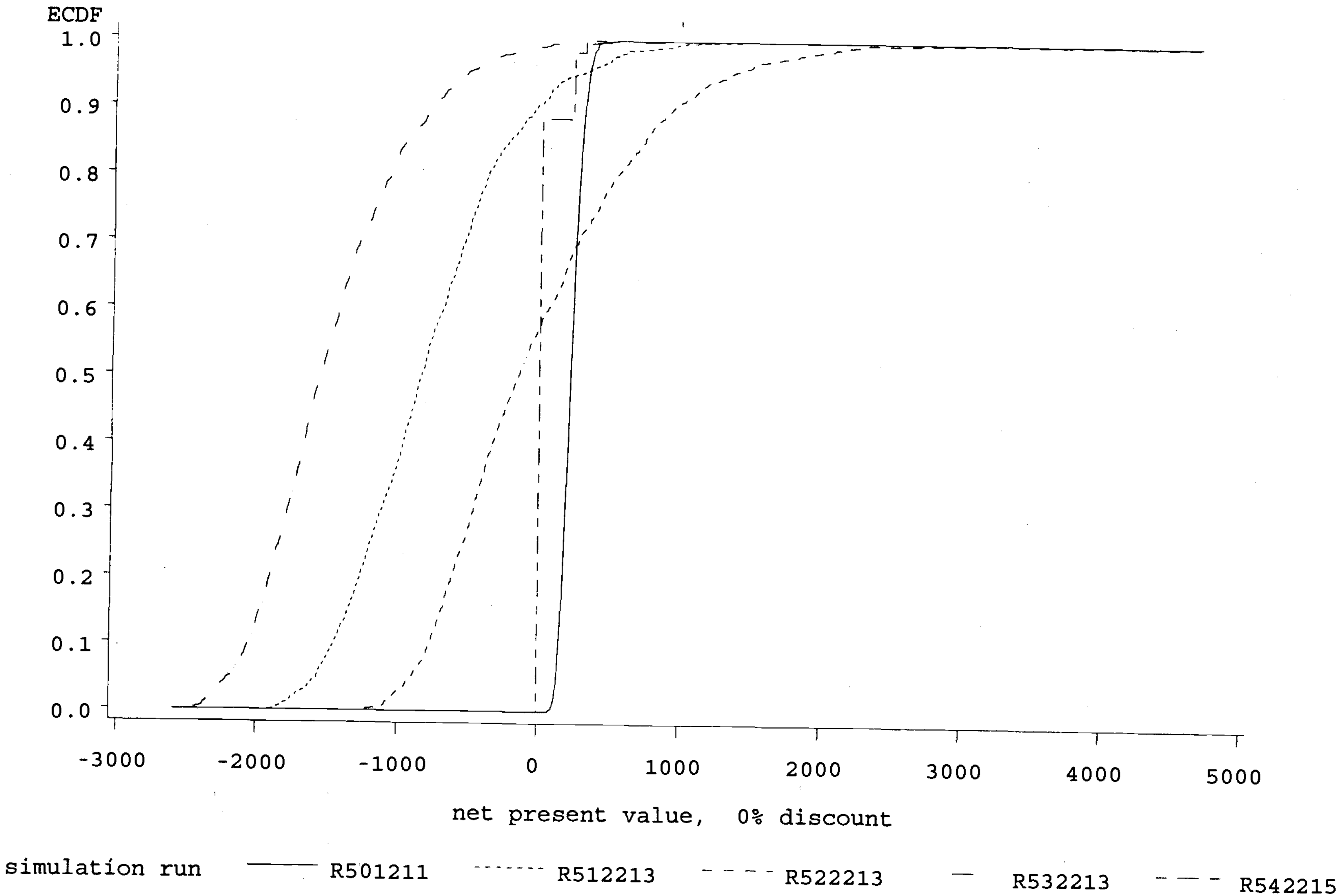
6.8. Appendices

6.8.1. Empirical Cumulative Distribution Functions for Net Present Value and Product Values from Management Scenarios for Stand 355, Diamond Lake Ranger District.

Key to Simulation Run Numbers

R501211 - Control 1 - No investment in management + minimum extraction
R512213 - Prescription 1
R522213 - Prescription 2
R532213 - Prescription 3
R542215 - Control 2 - No investment in management + maximum extraction



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net present value, 0% discount
simulation run
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R512213
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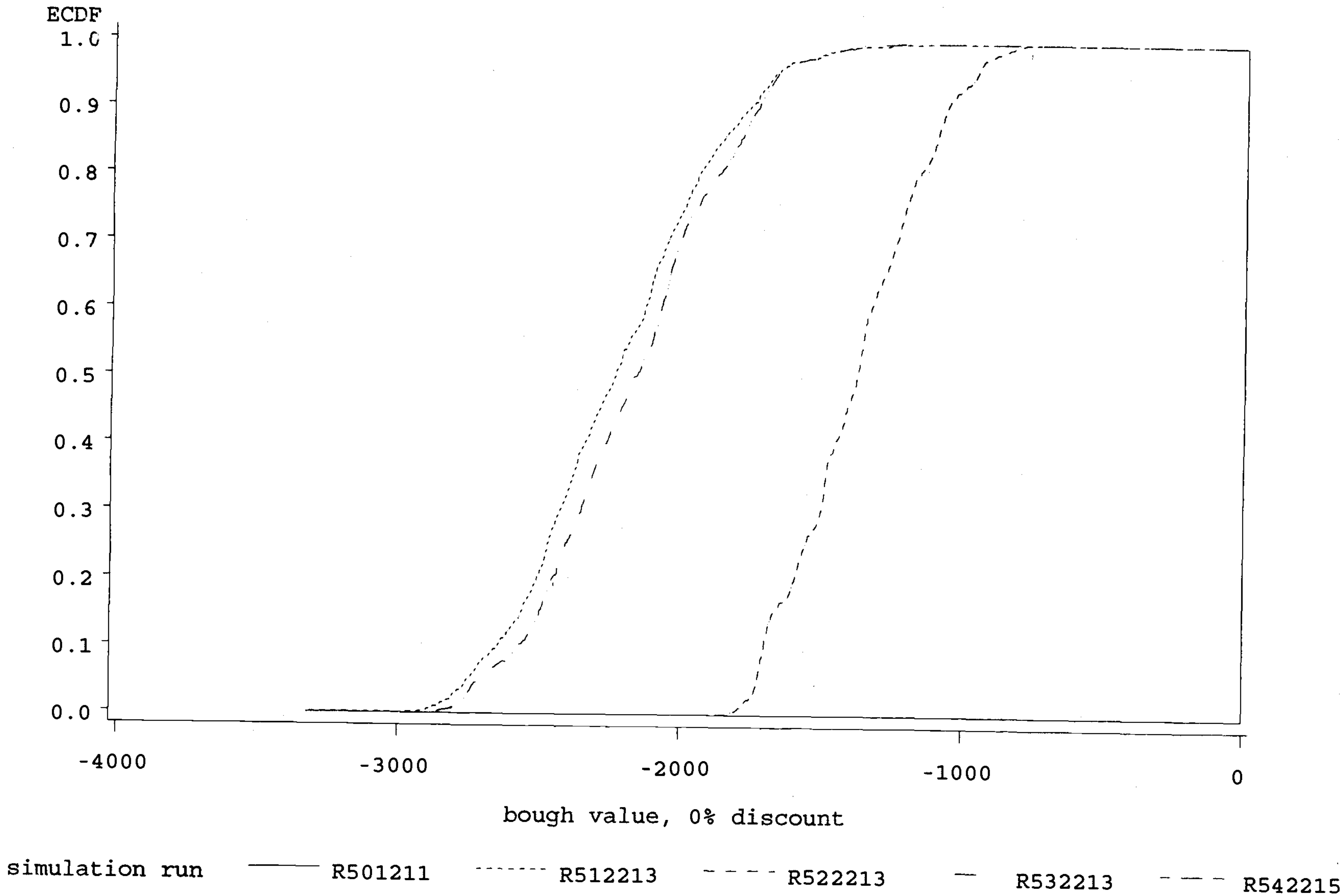
R532213
R542215



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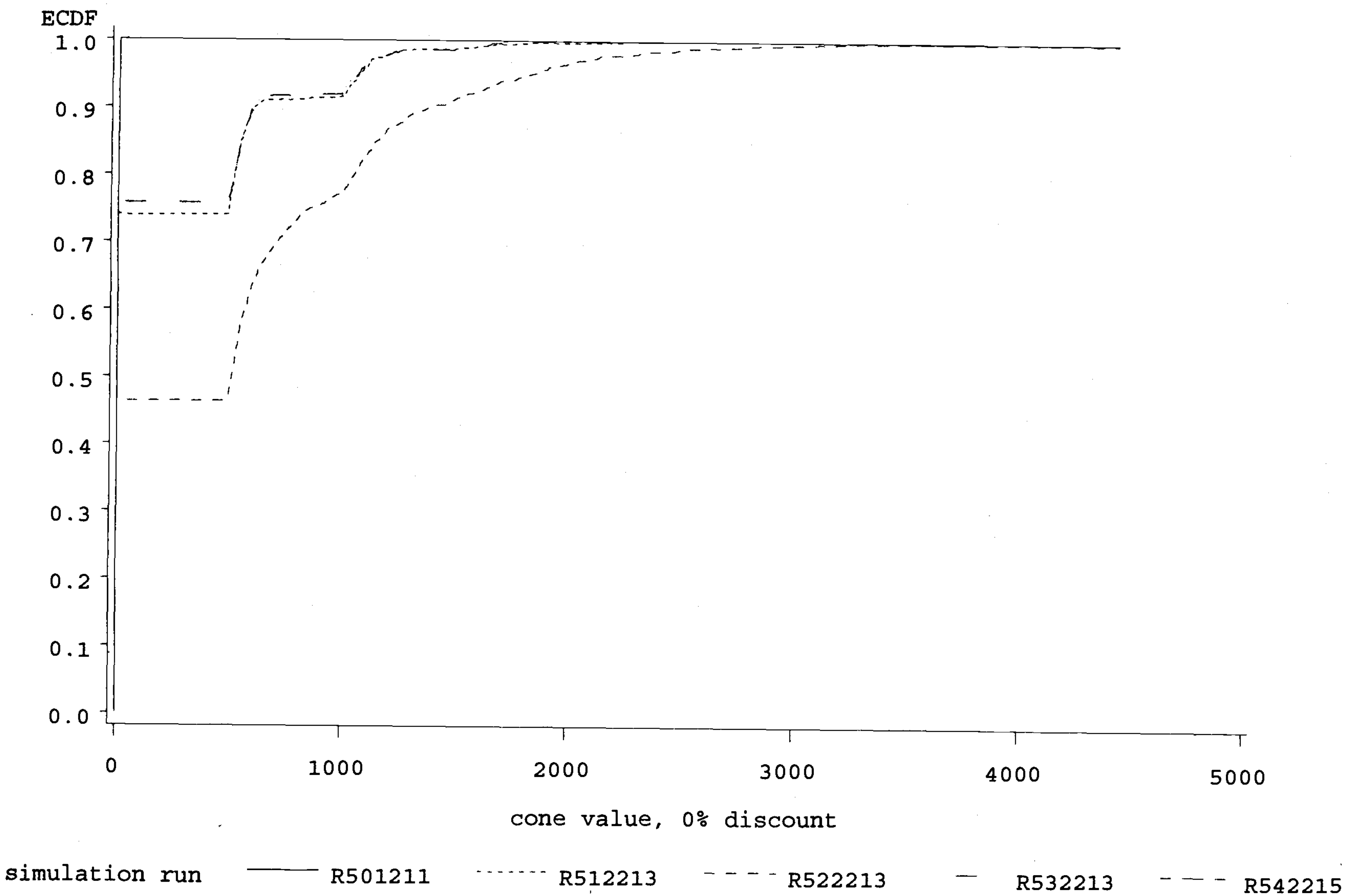

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cone value, 0% discount
simulation run
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R512213
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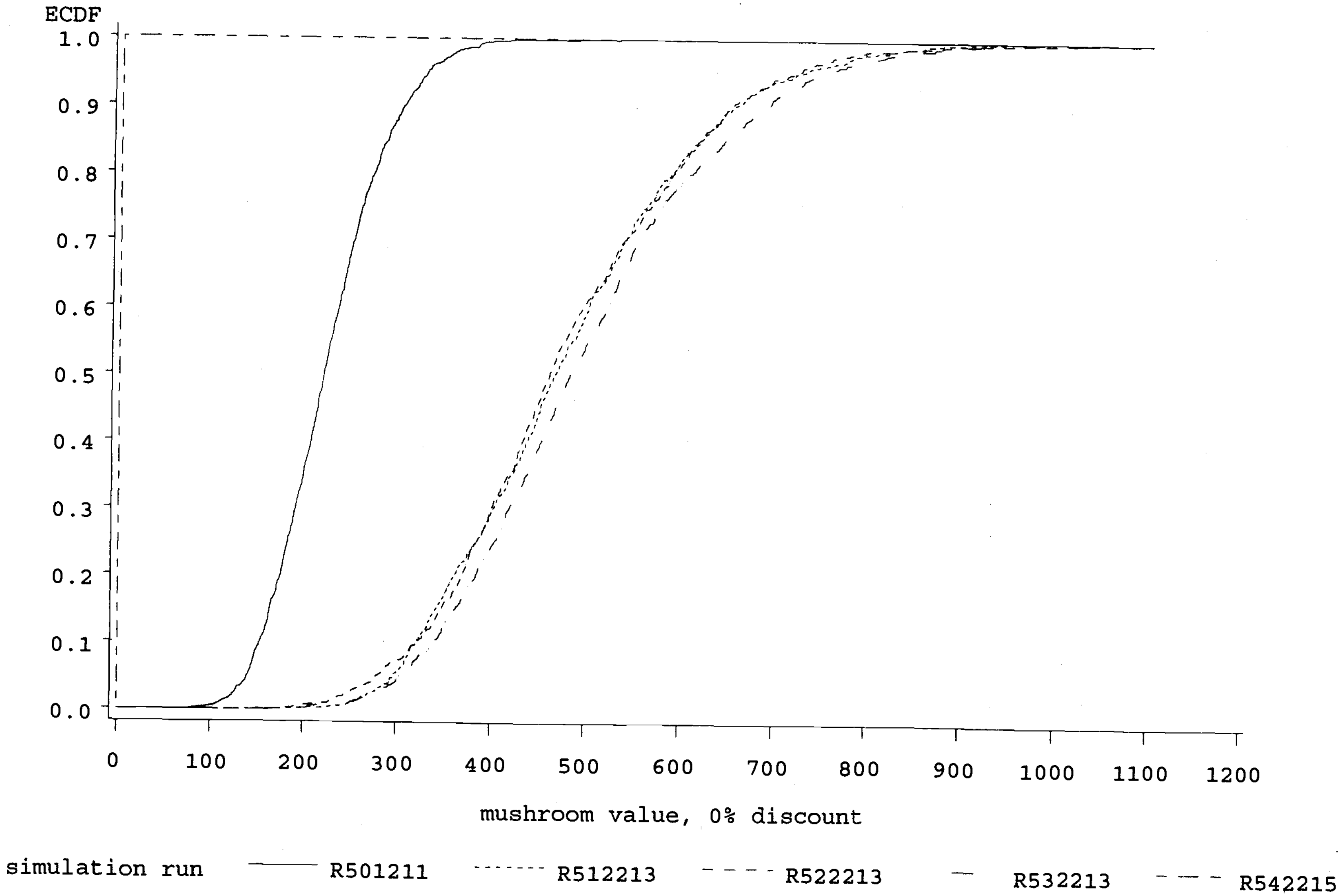

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mushroom value, 0% discount
simulation run
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R512213
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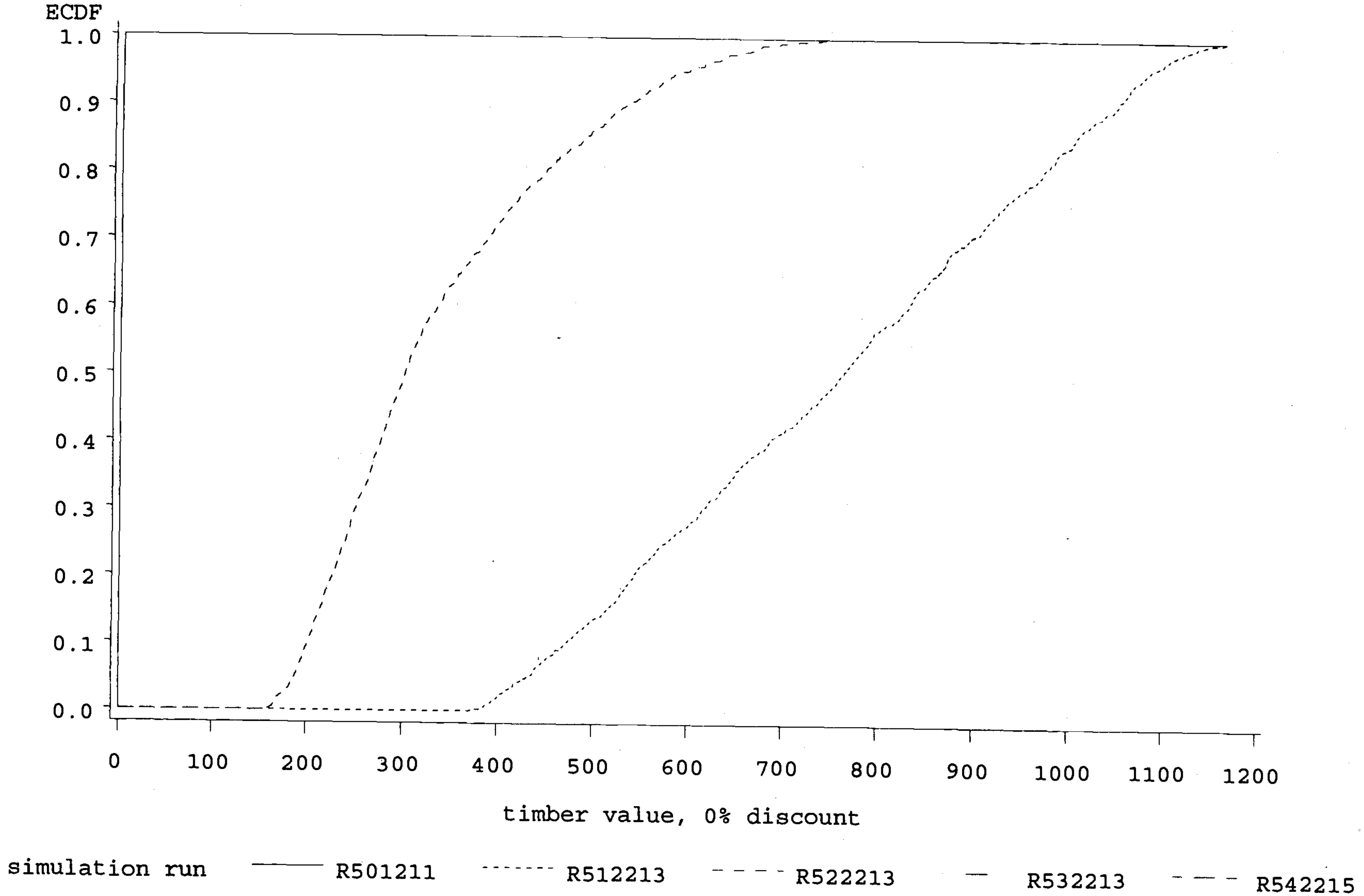
R542215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timber value, 0% discount
simulation run
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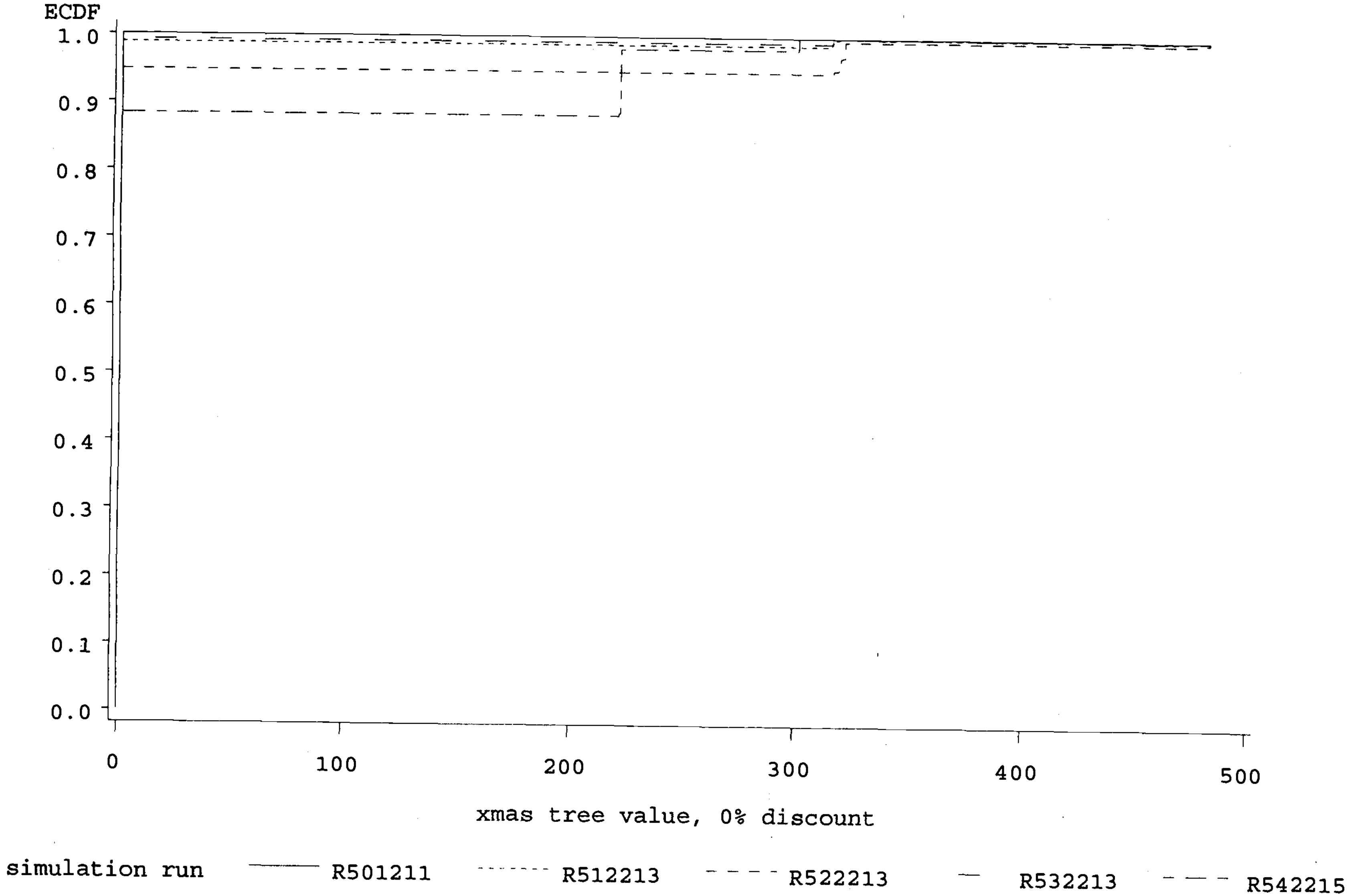
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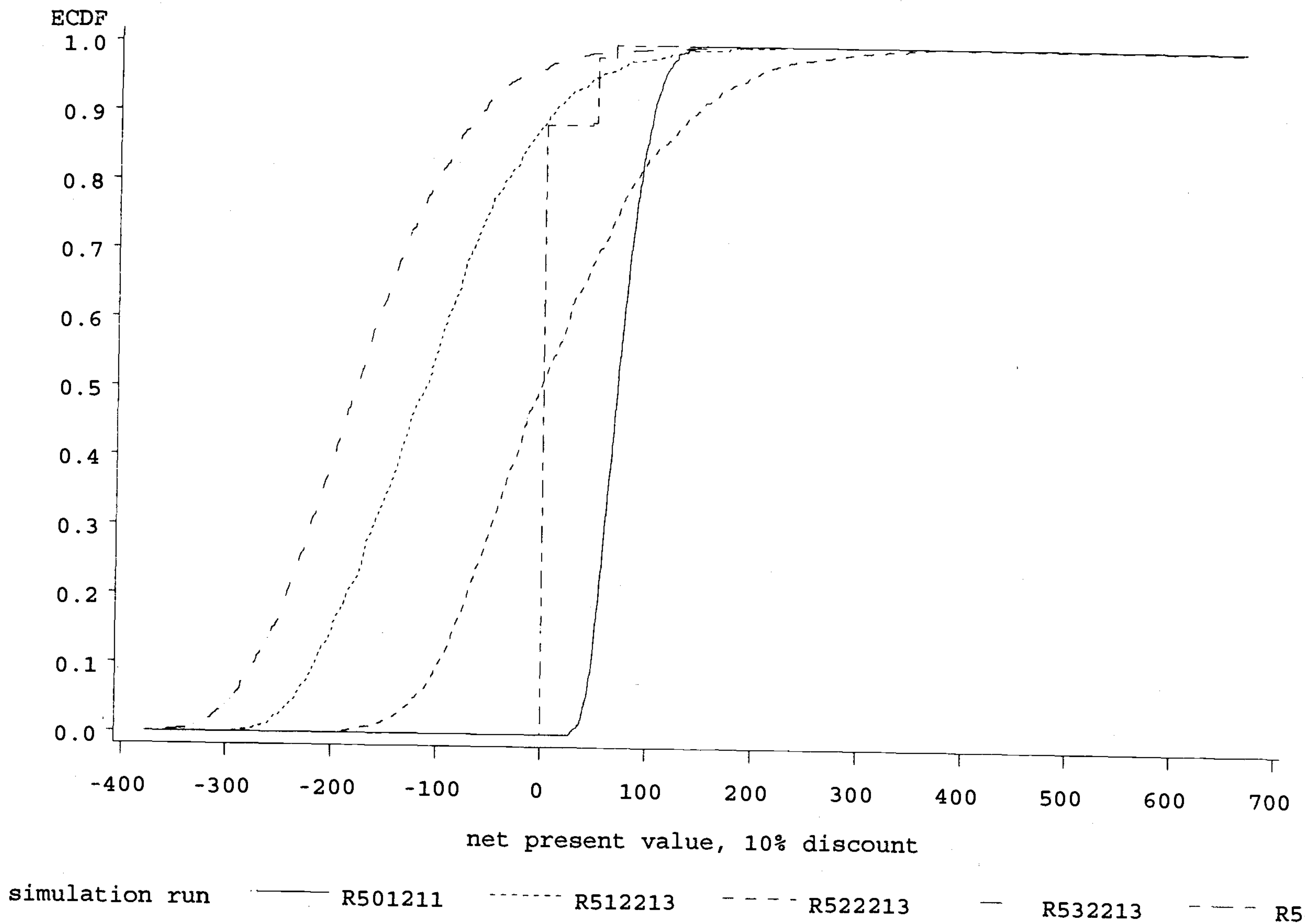
xmas tree value, 0% discount
simulation run
R501211
R512213
R522213
R532213
R542215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net present value, 10% discount
simulation run
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R512213
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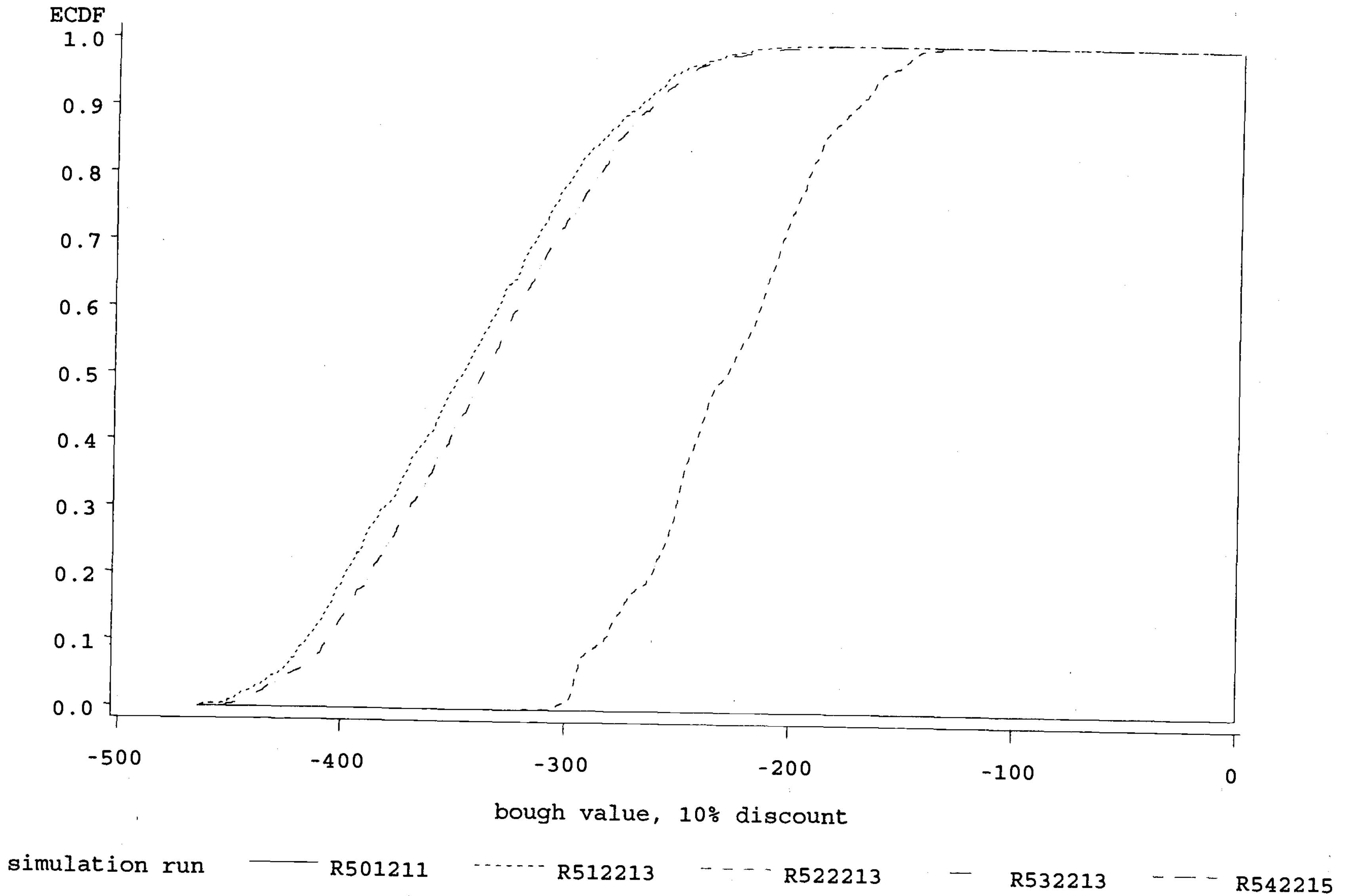
R532213
R542215



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bough value, 10% discount
simulation run
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R512213
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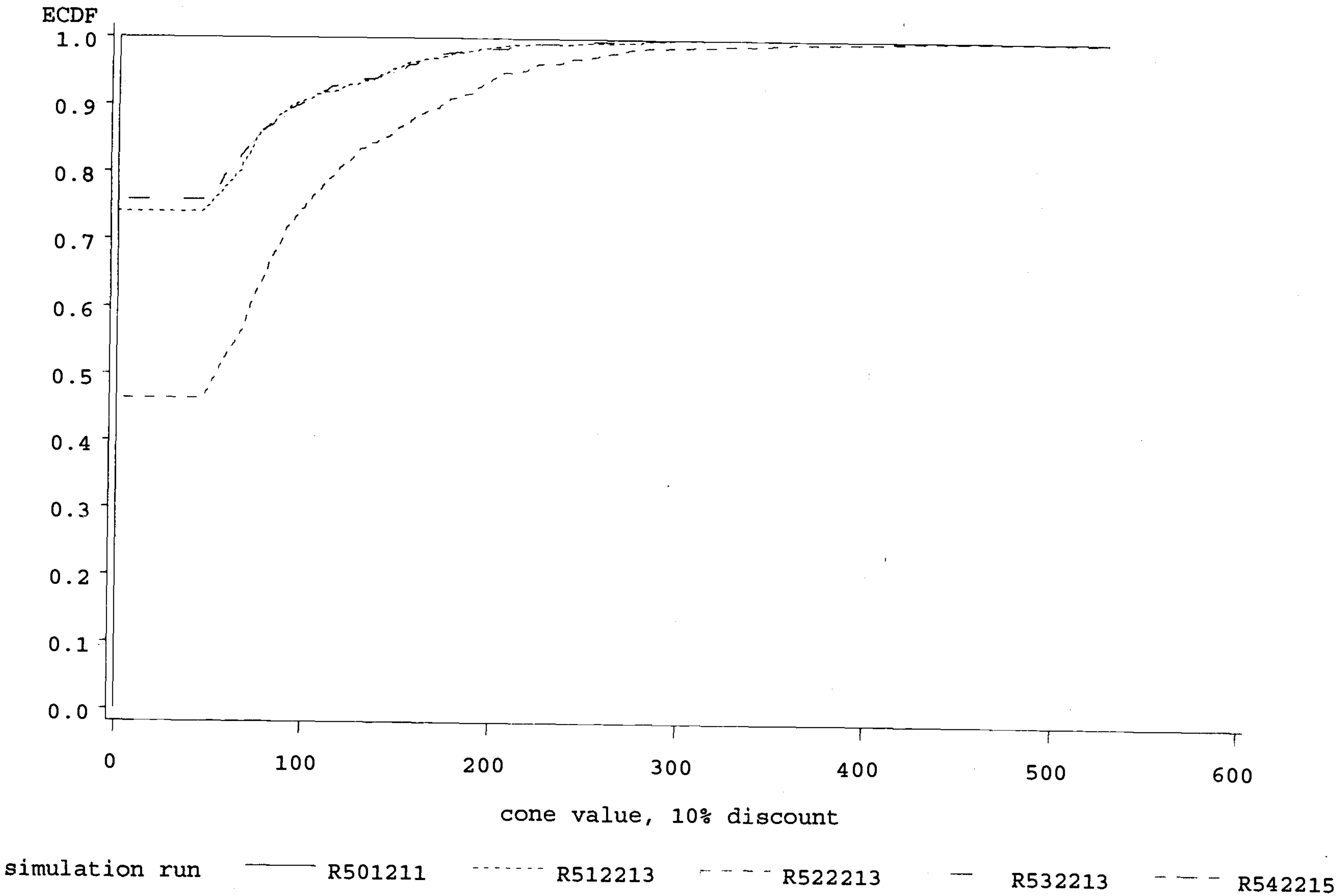
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cone value, 10% discount
simulation run
R501211
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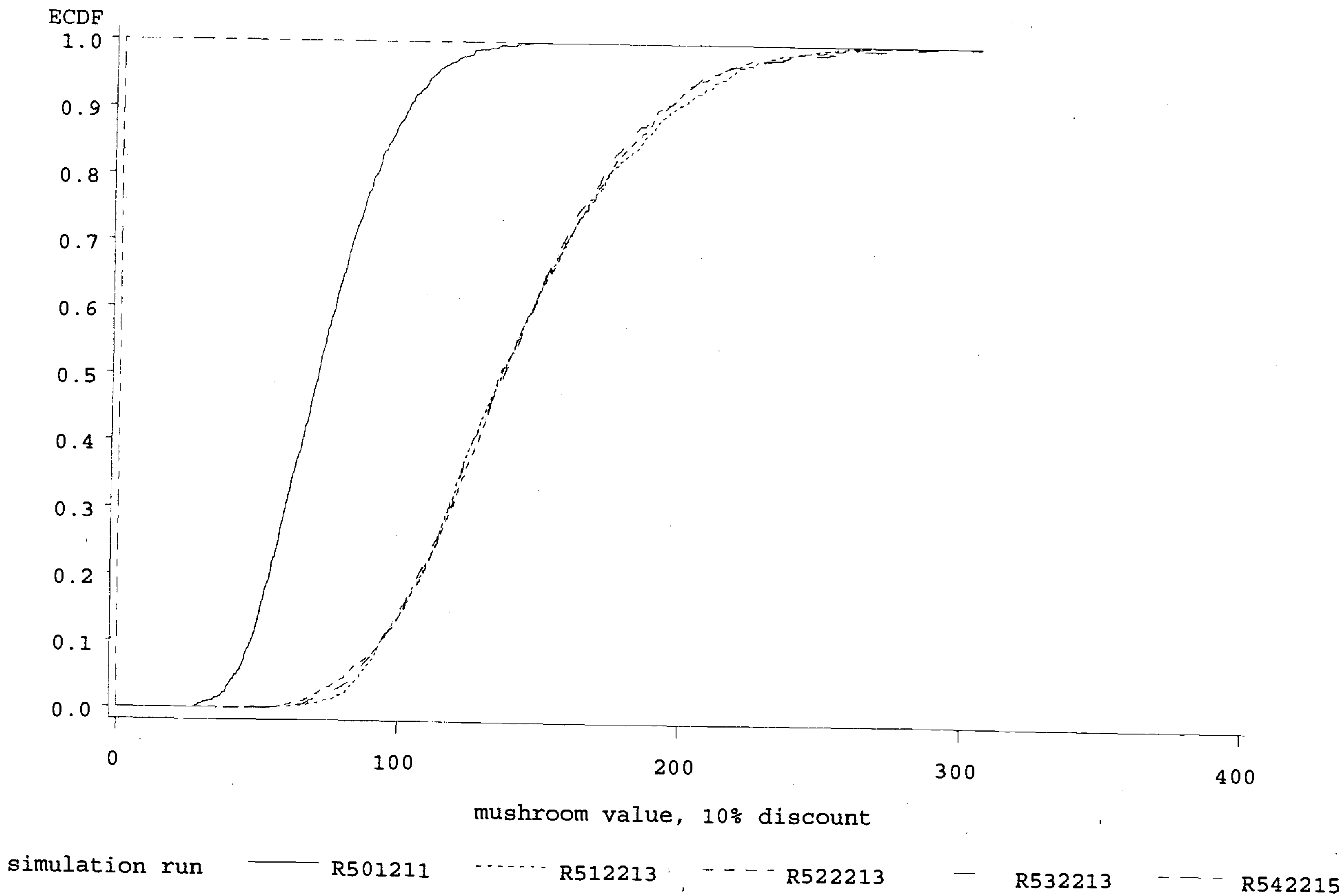
R542215



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mushroom value, 10% discount
simulation run
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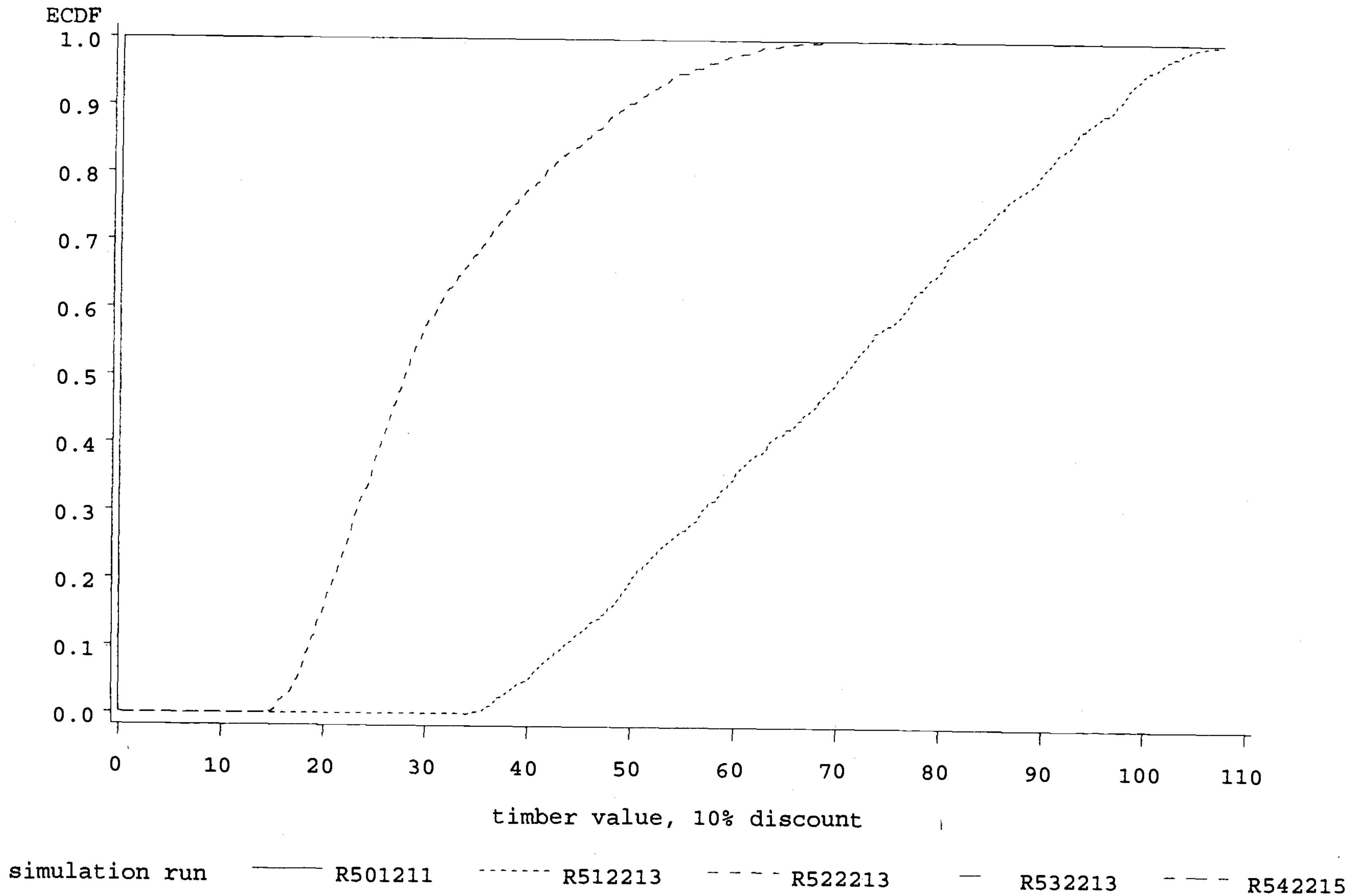
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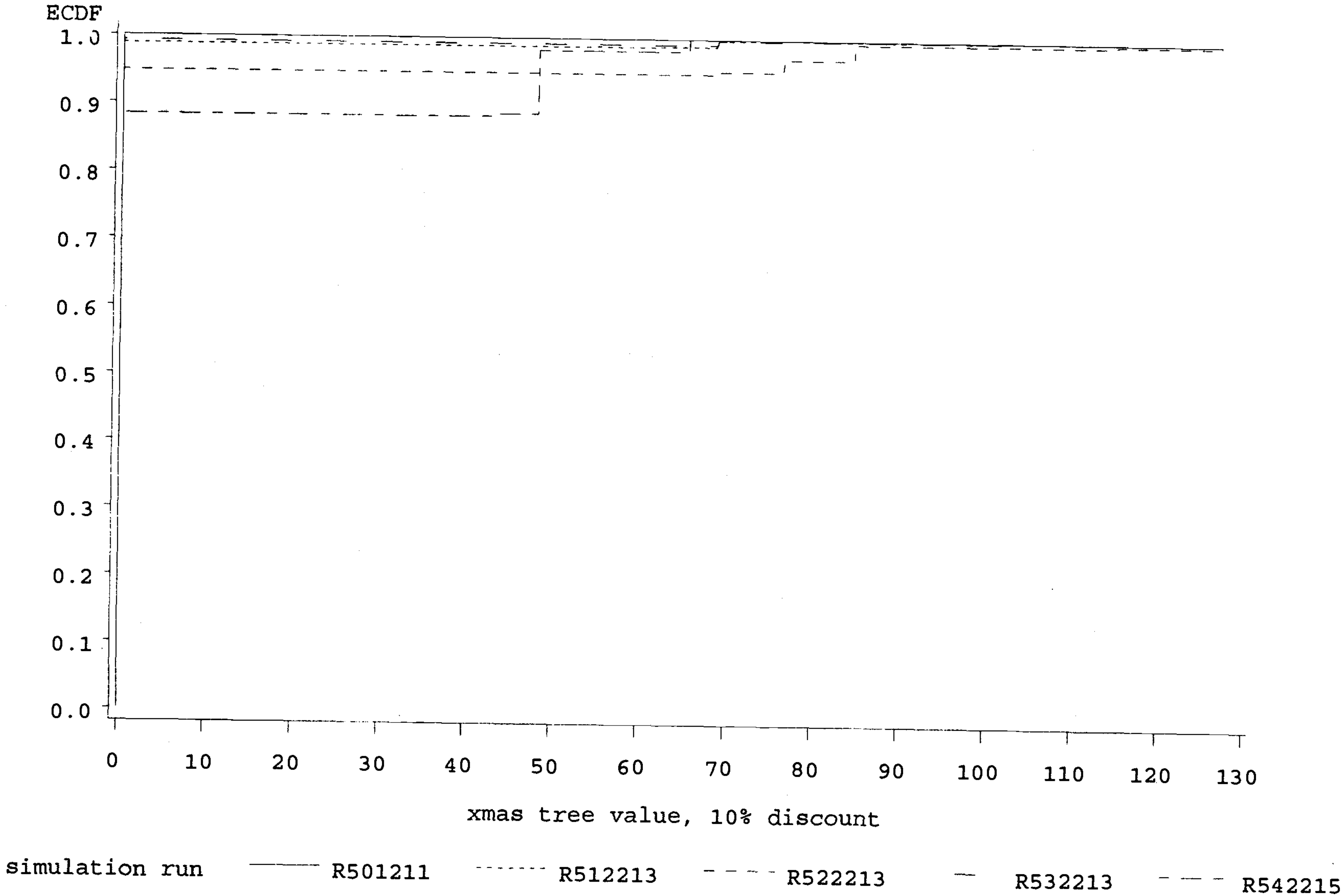
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xmas tree value, 10% discount
simulation run
R501211
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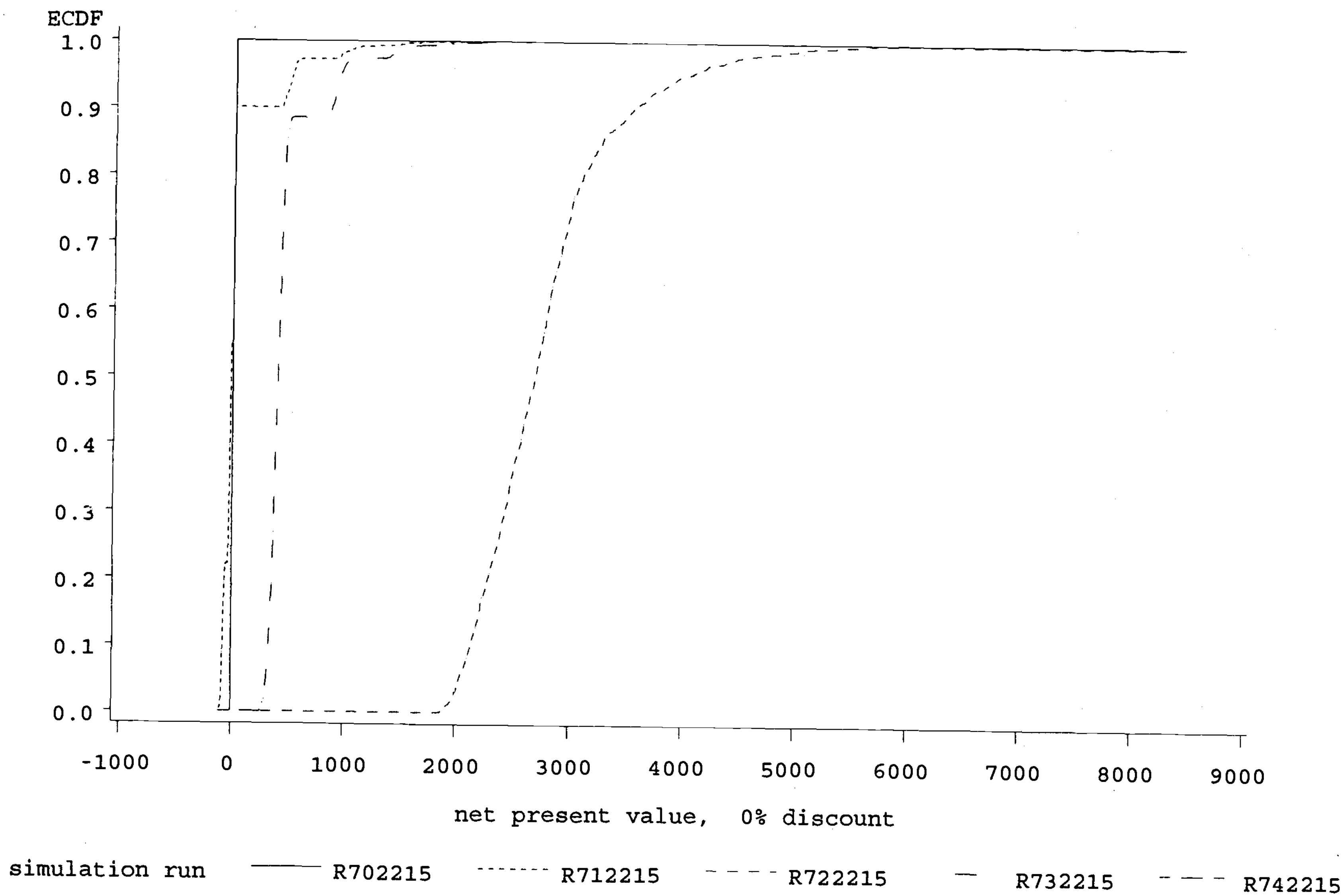
R522213
R532213
R542215

Appendix 6.8.2. Empirical Cumulative Distribution Functions for Net Present Value and Product Values from Management Scenarios for Stand 357, Diamond Lake Ranger District.

Key to Simulation Run Numbers

R702215 - Control 1 - No investment in management + minimum extraction
R712215 - Prescription 1
R722215 - Prescription 2
R732215 - Prescription 3
R742215 - Control 2 - No investment in management + maximum extraction



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simulation run
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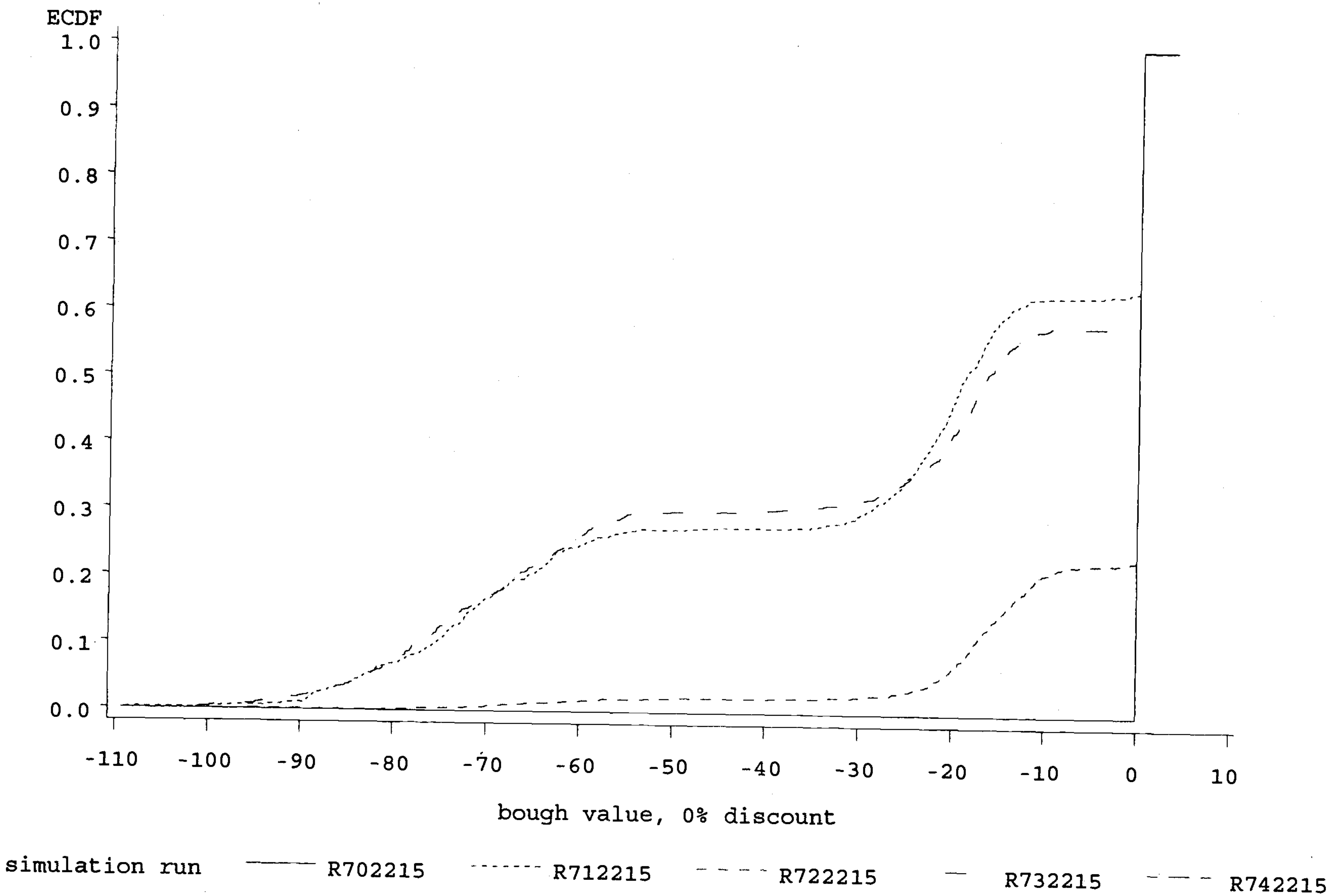

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bough value, 0% discount
simulation run
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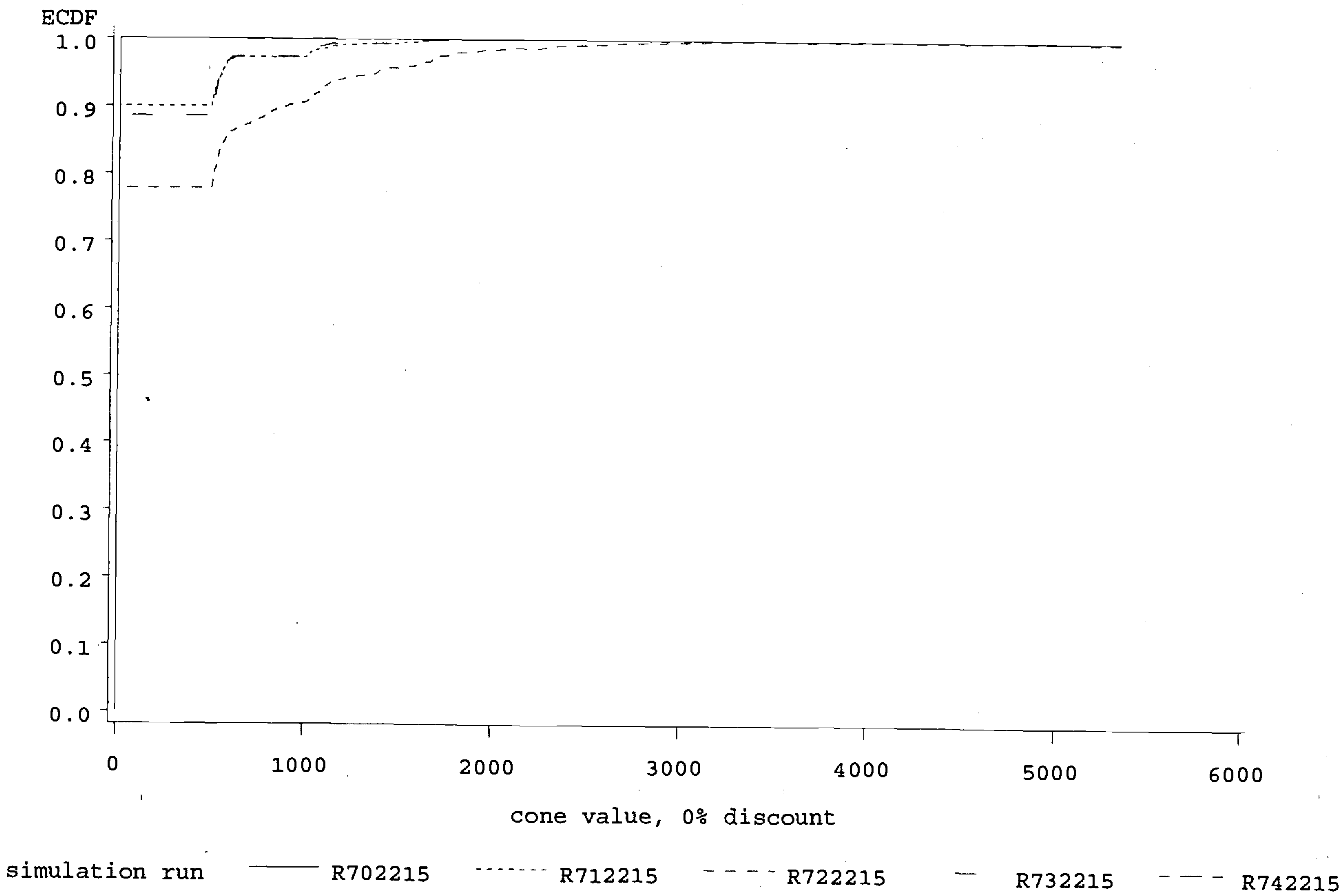

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cone value, 0% discount
simulation run
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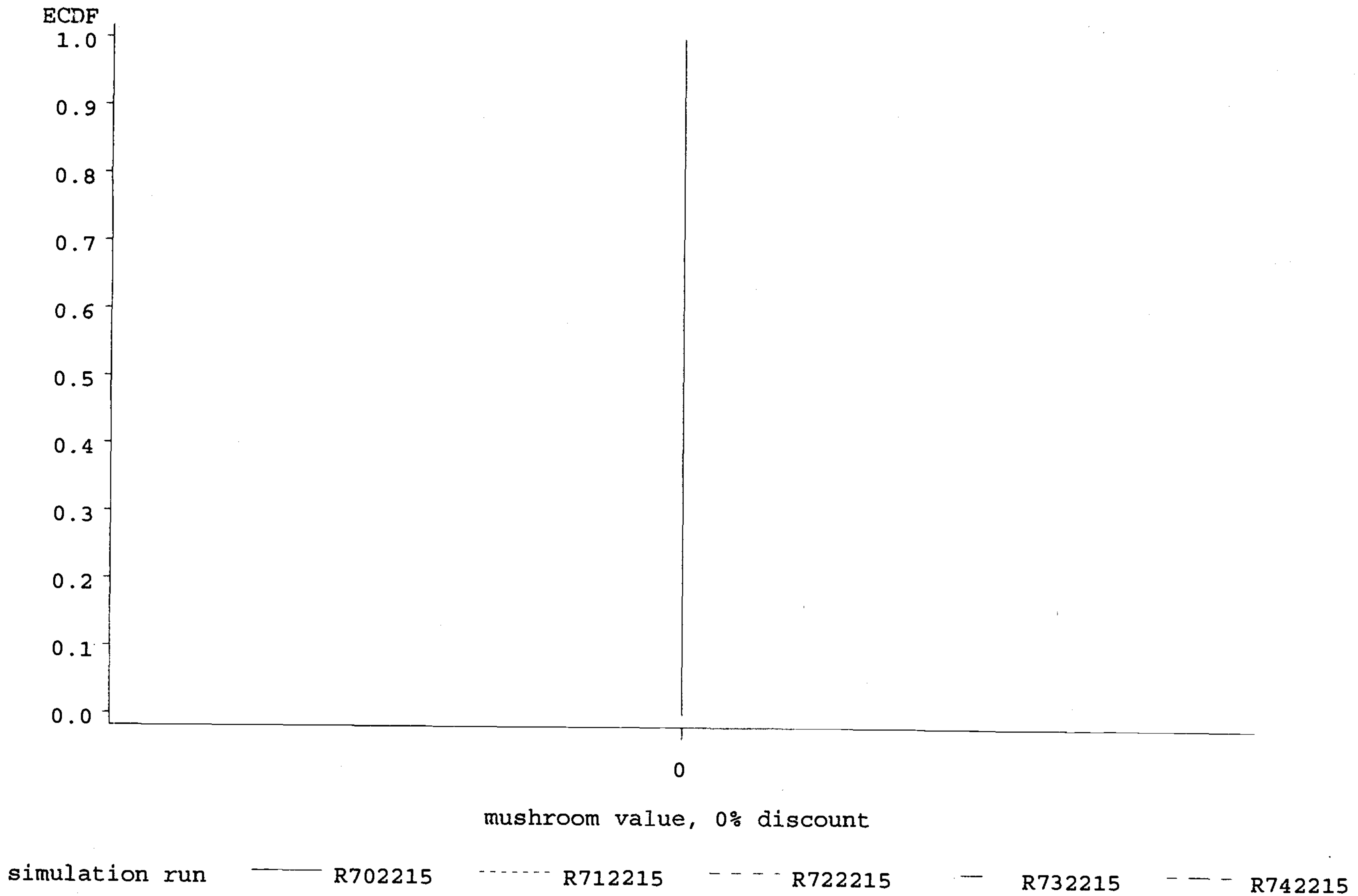

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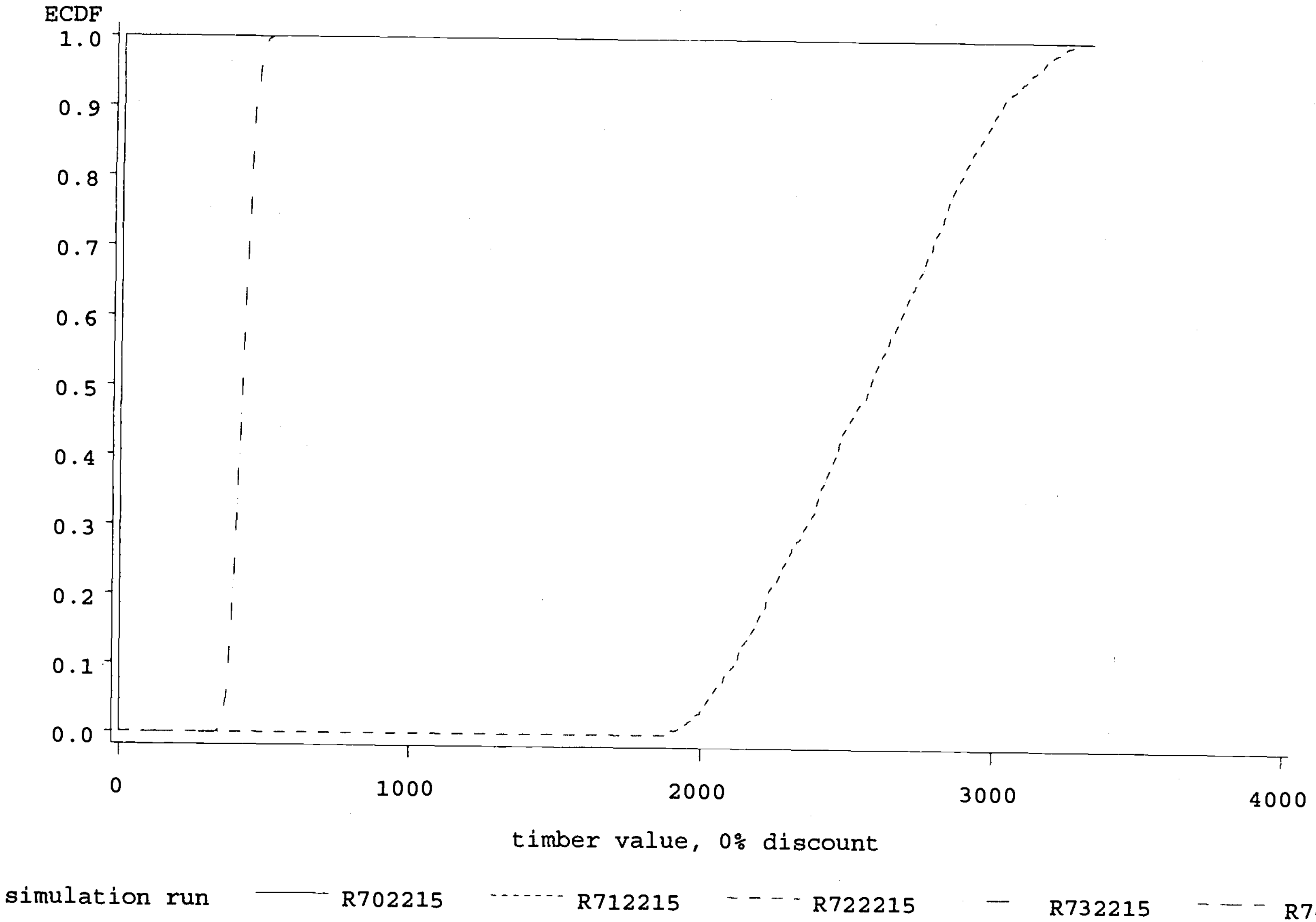
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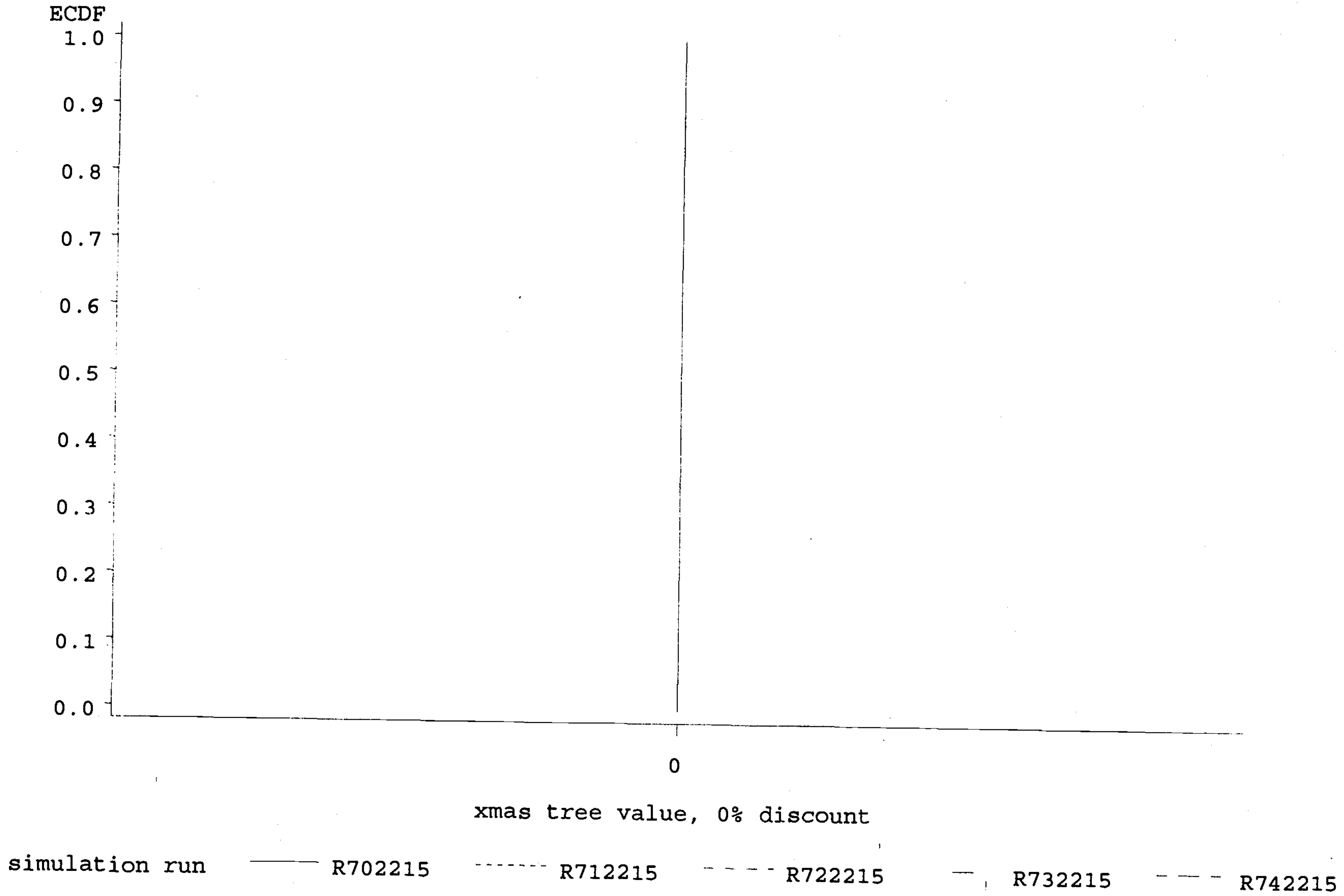
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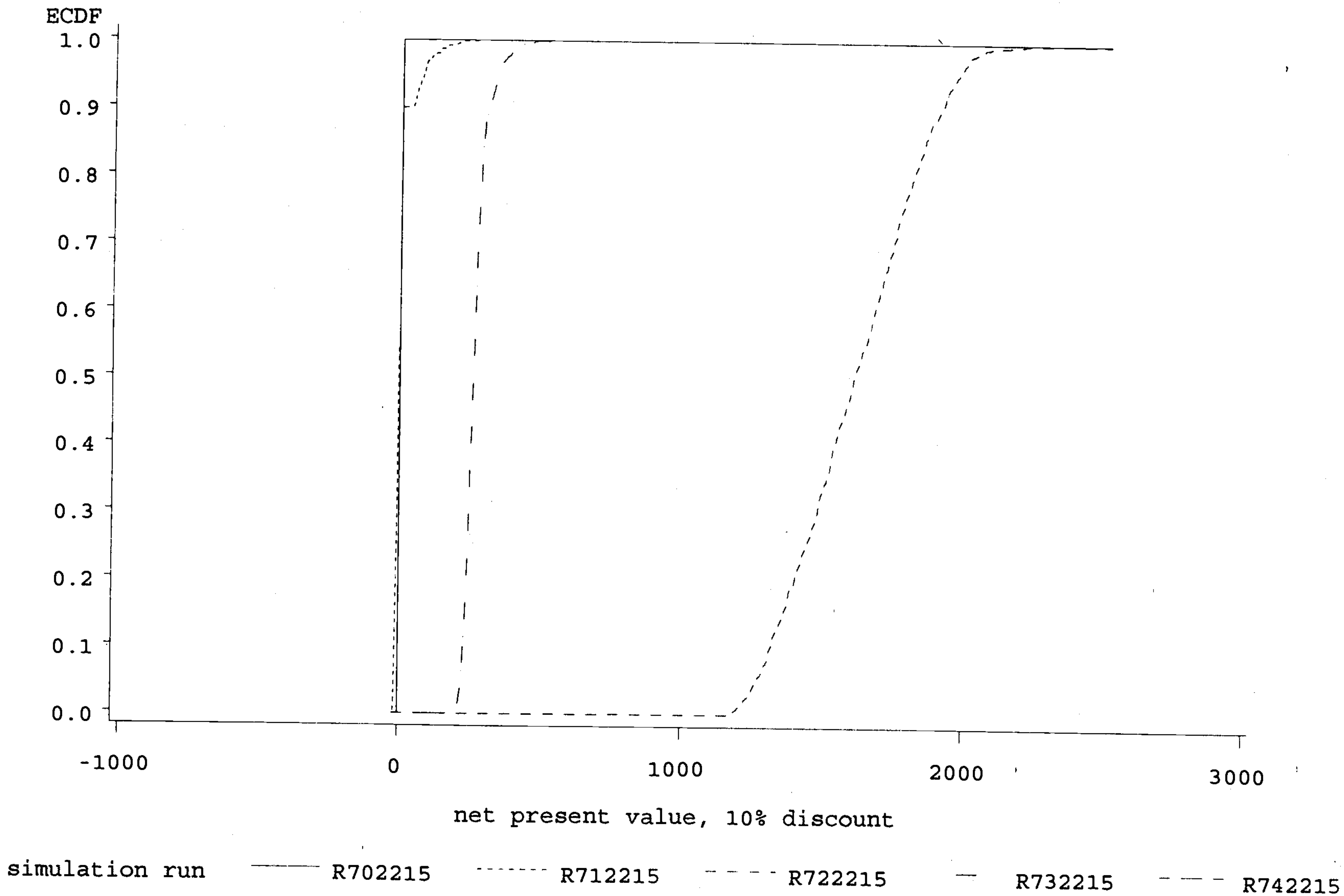

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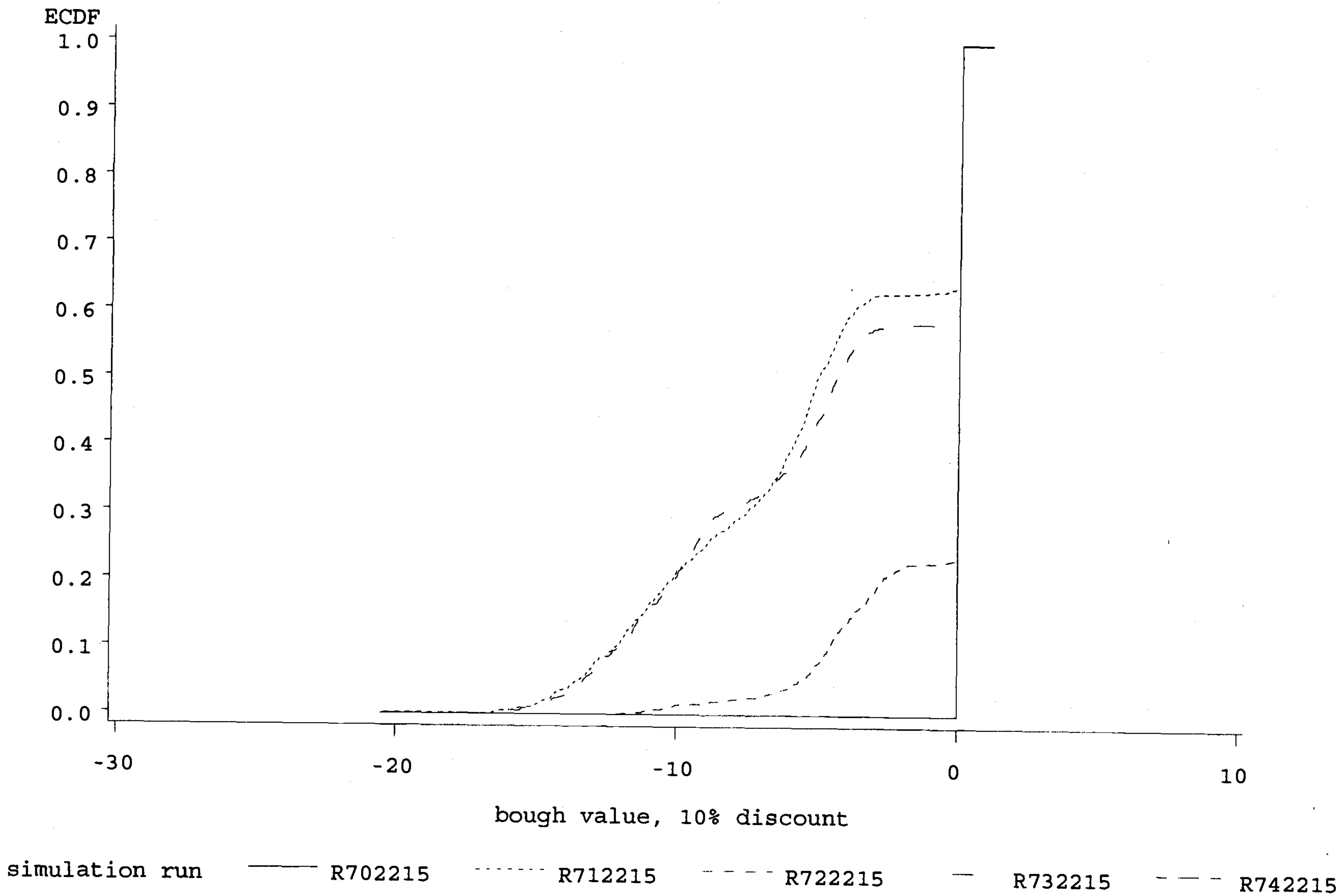
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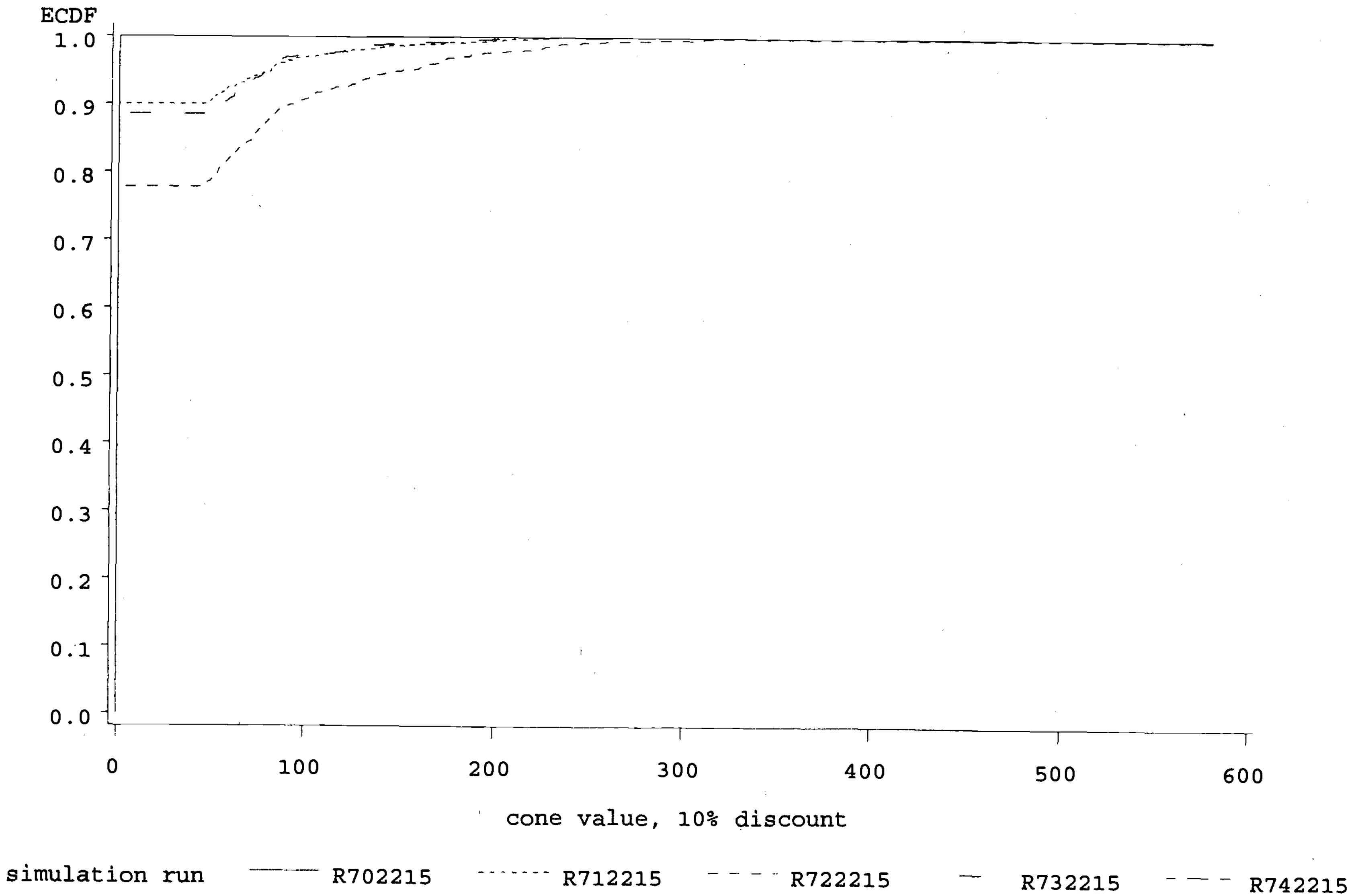

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cone value, 10% discount
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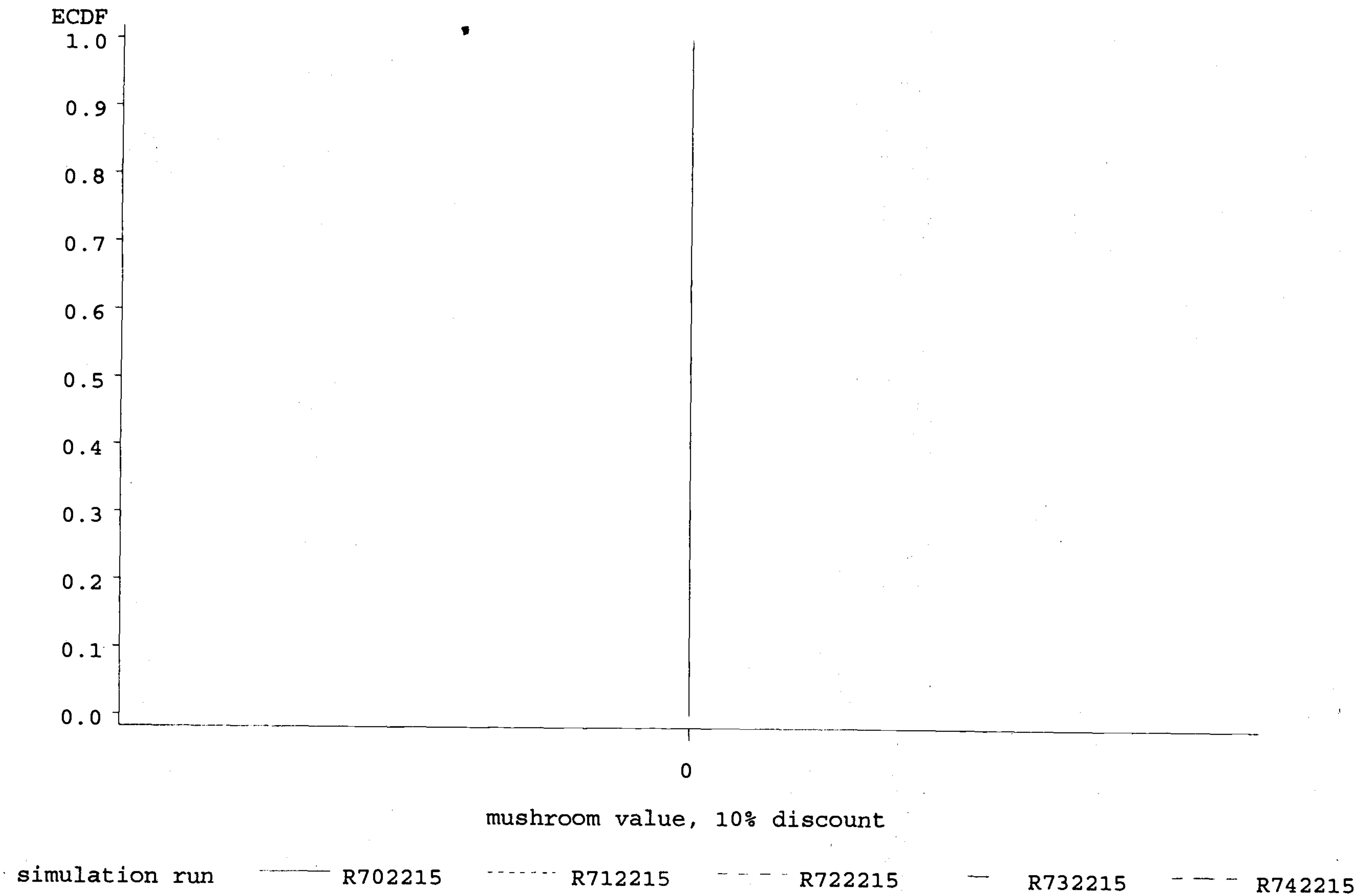
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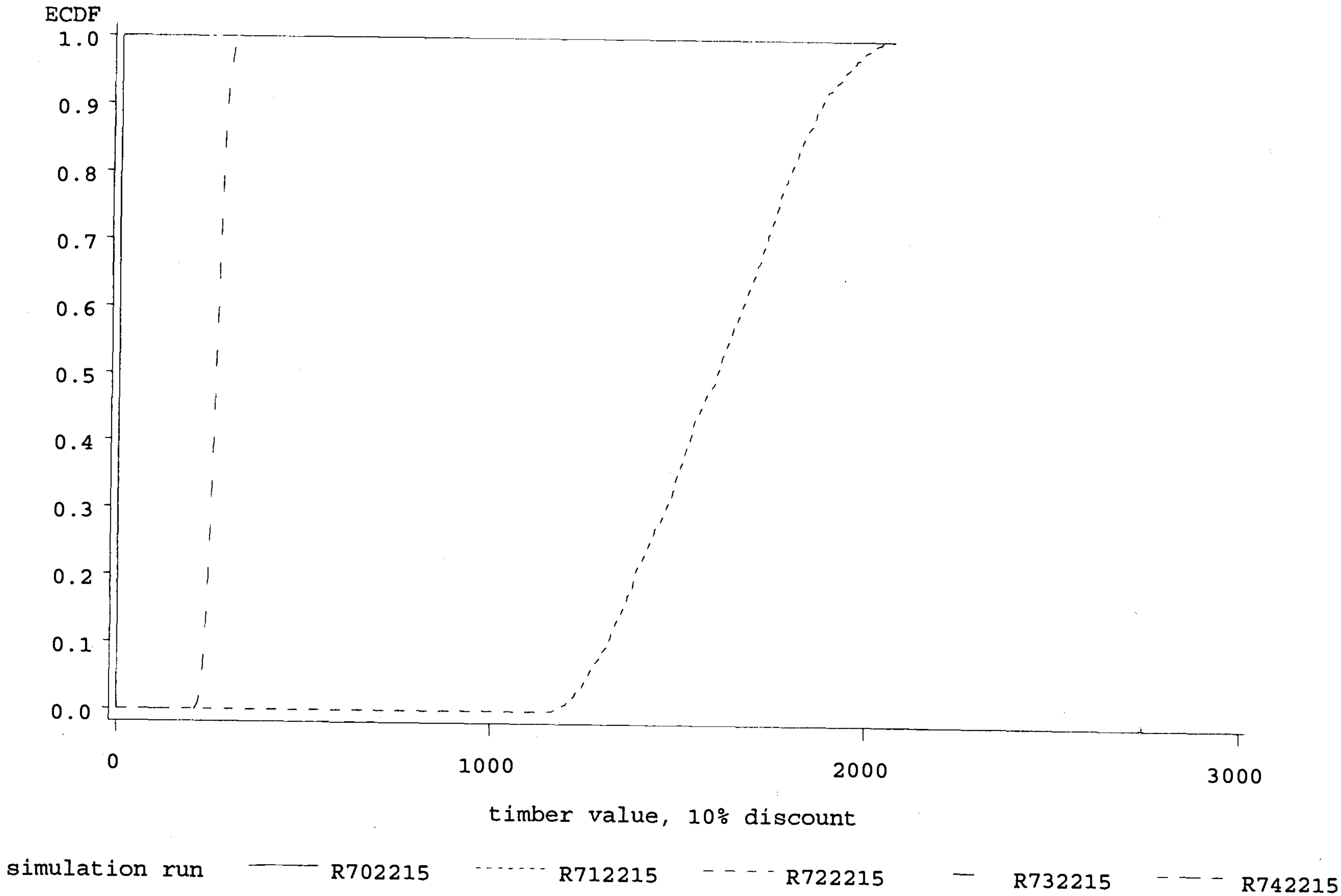

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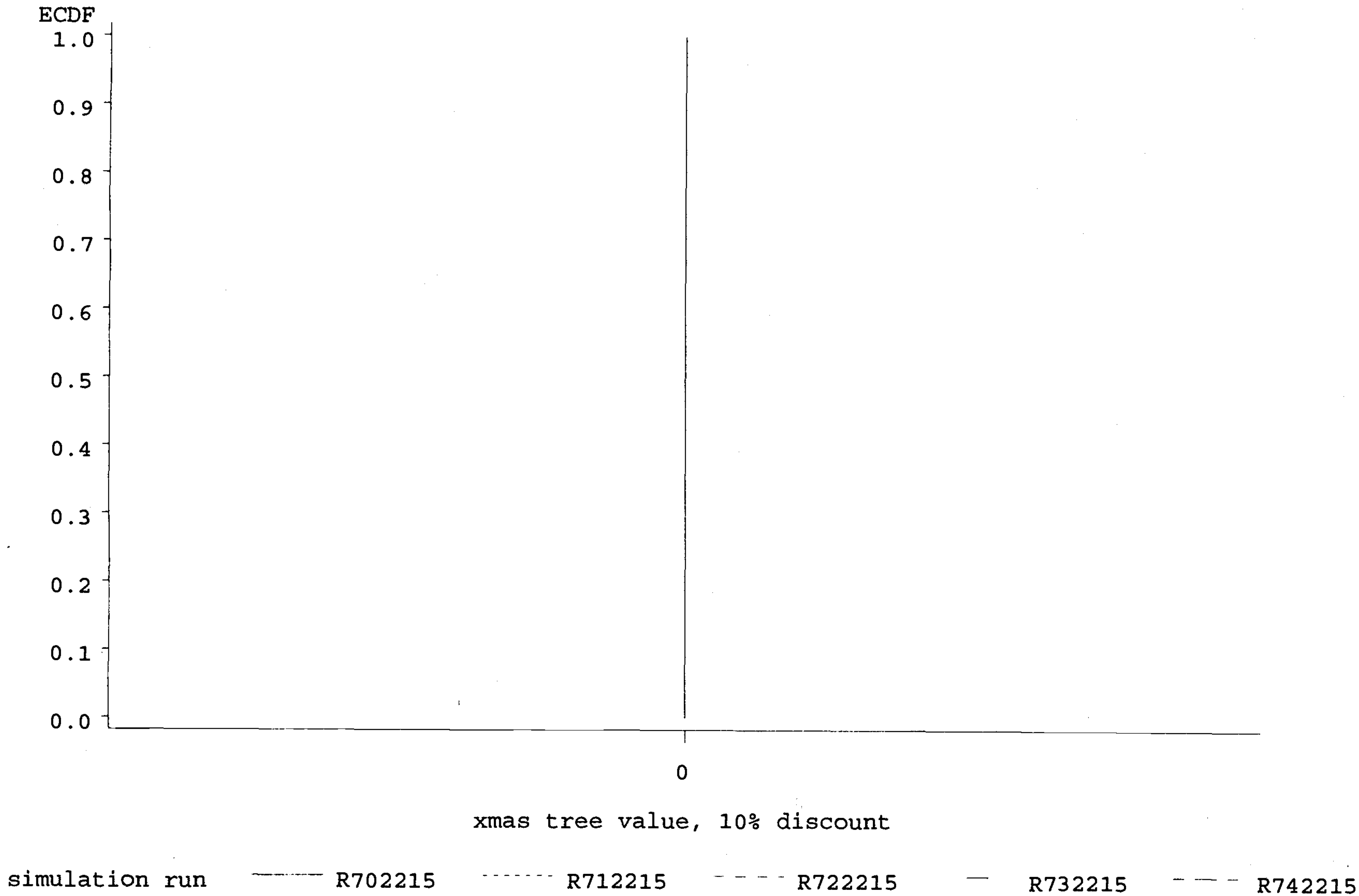
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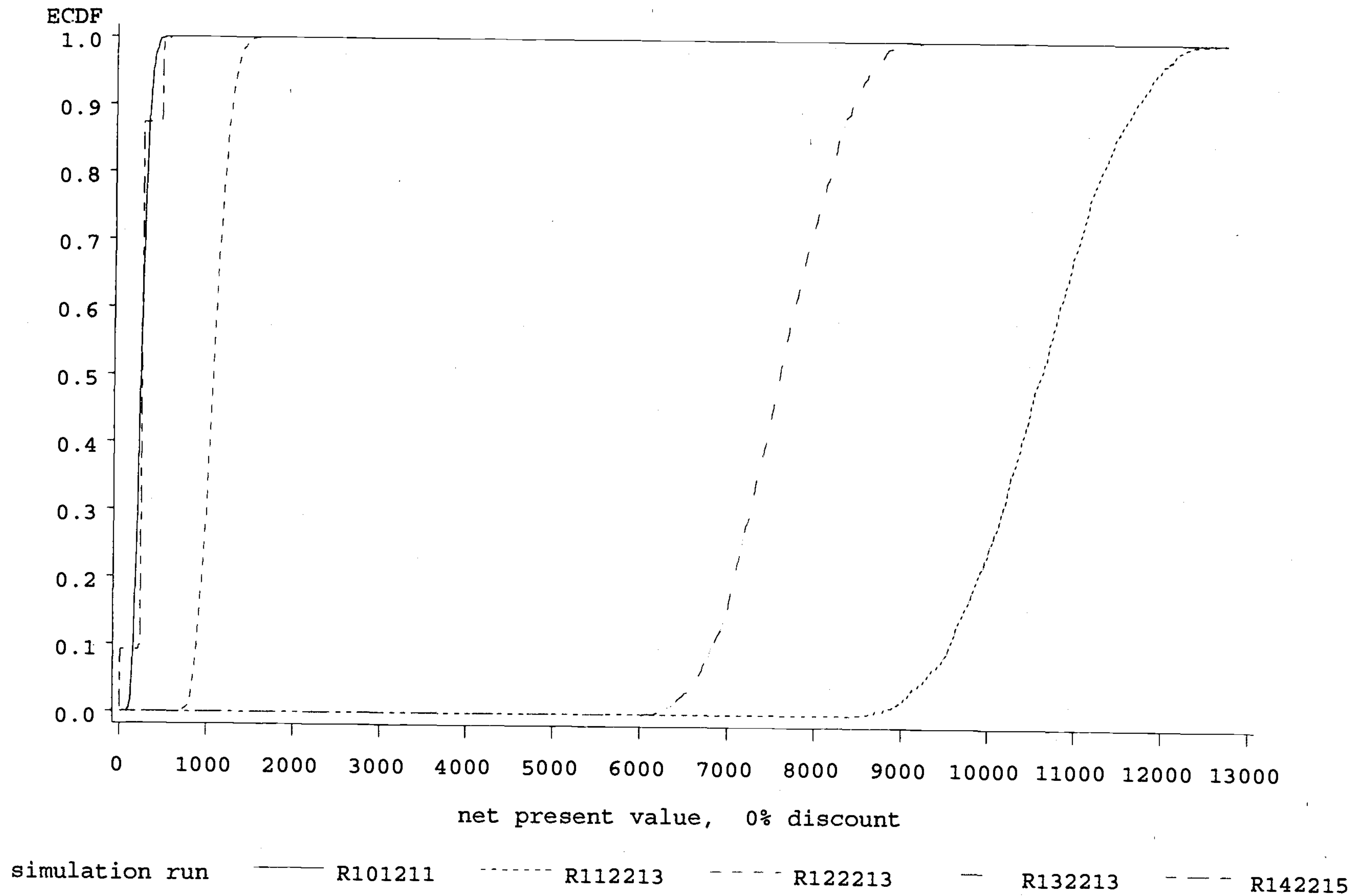
Appendix 6.8.3. Empirical Cumulative Distribution Functions for Net Present Value and Product Values from Management Scenarios for Stand 401, Diamond Lake Ranger District.

Key to Simulation Run Numbers

R101211 - Control 1 - No investment in management + minimum extraction
R112213 - Prescription 1
R122213 - Prescription 2
R132213 - Prescription 3
R142215 - Control 2 - No investment in management + maximum extraction



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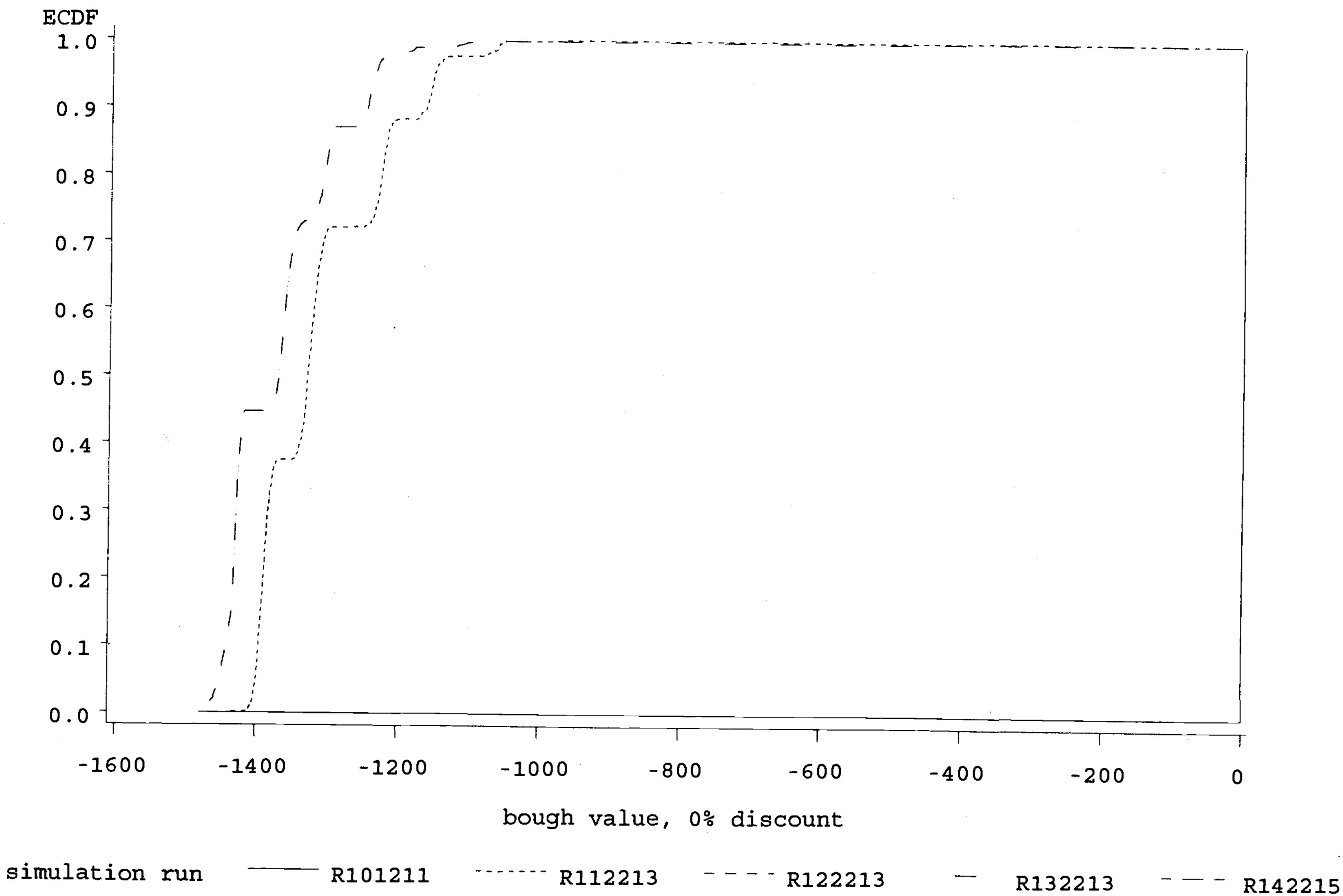
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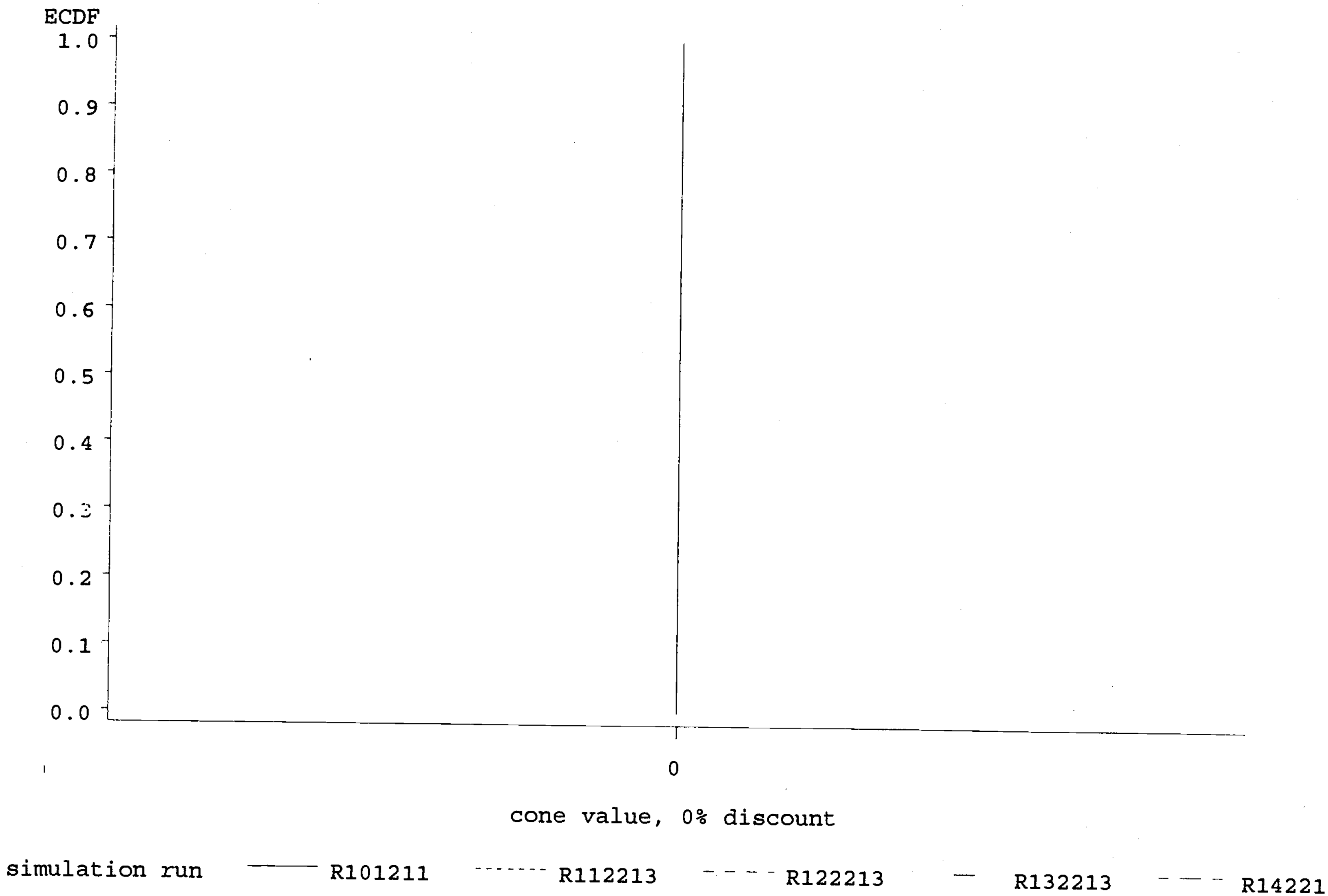
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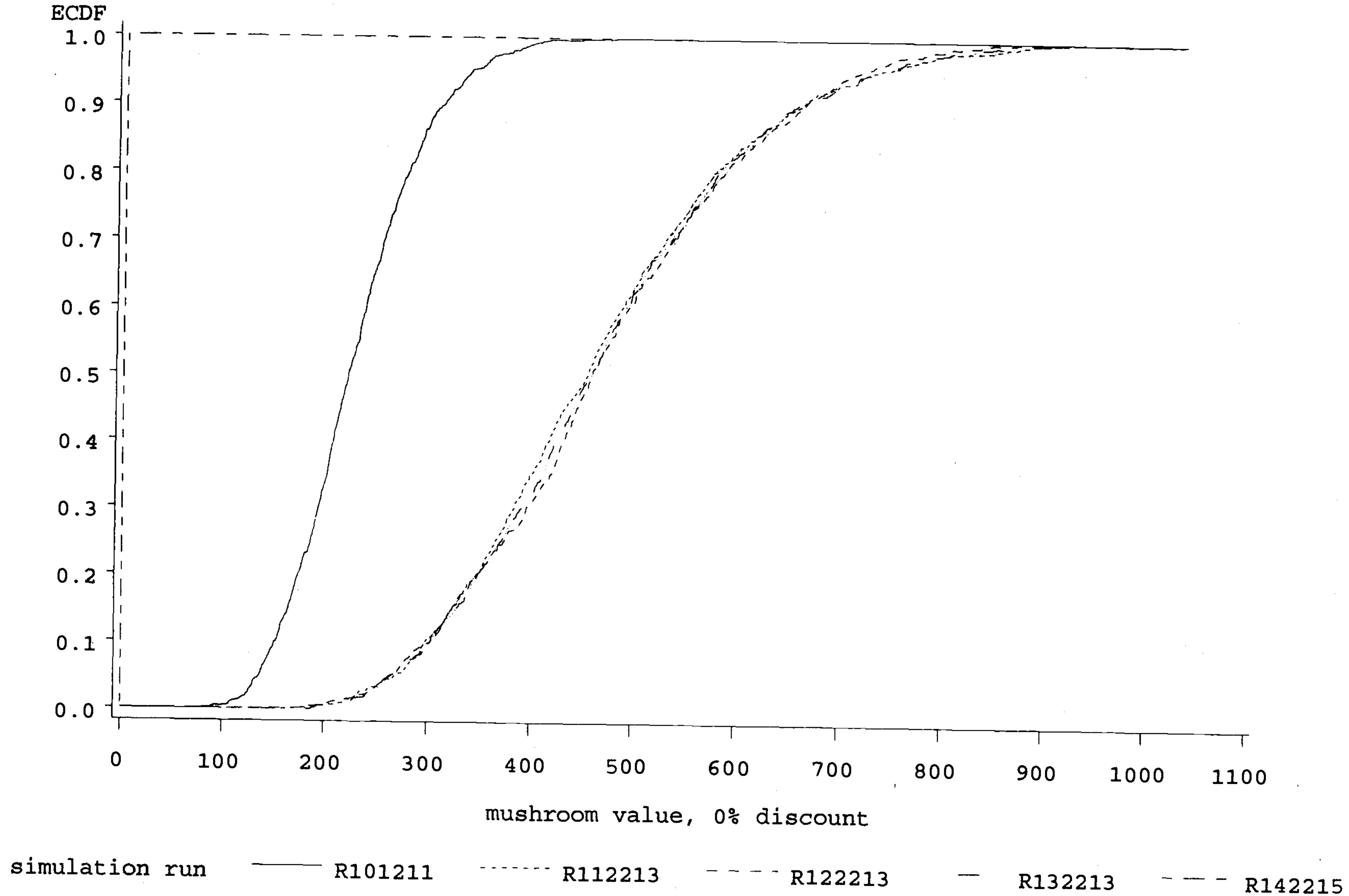

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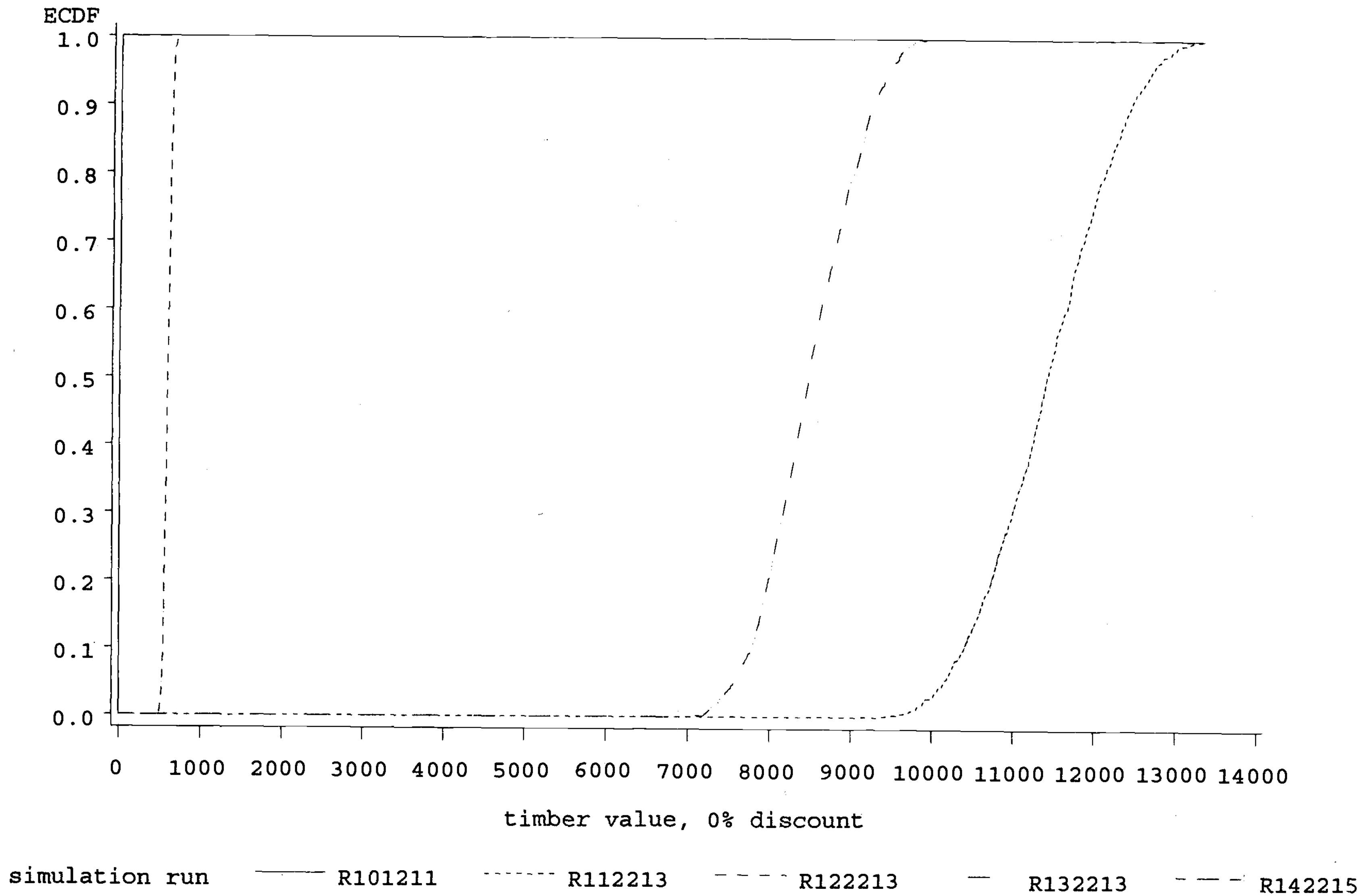
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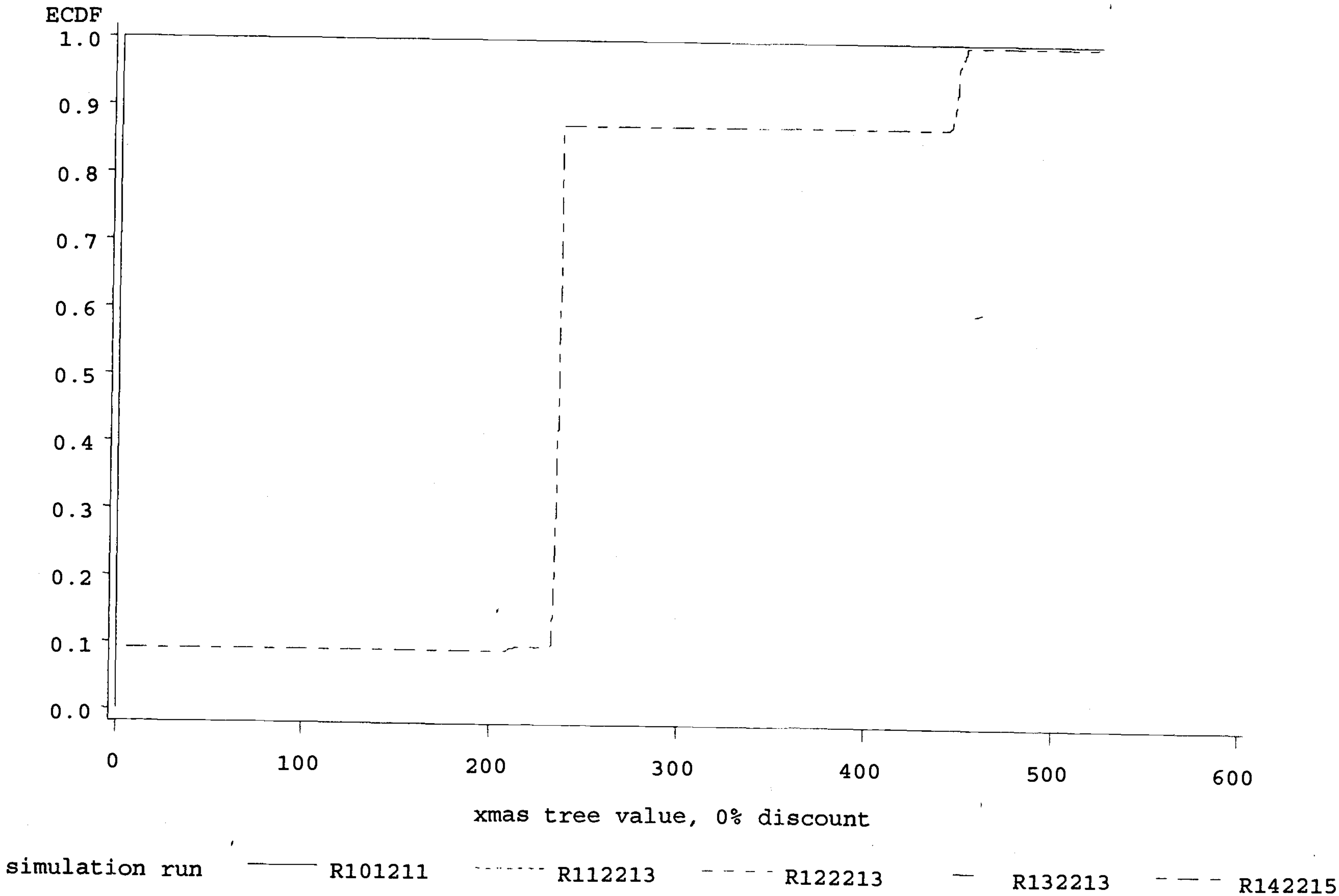
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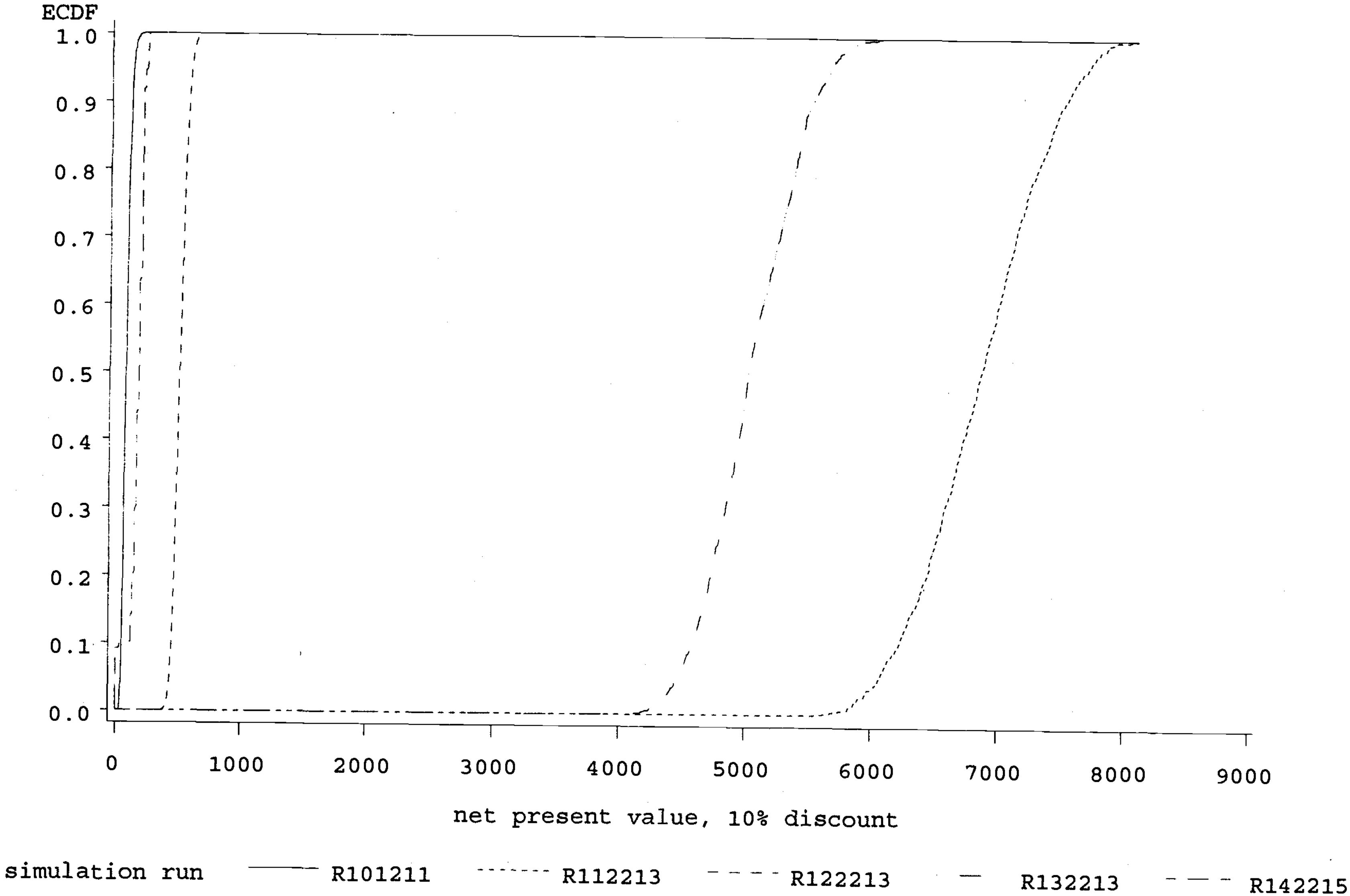
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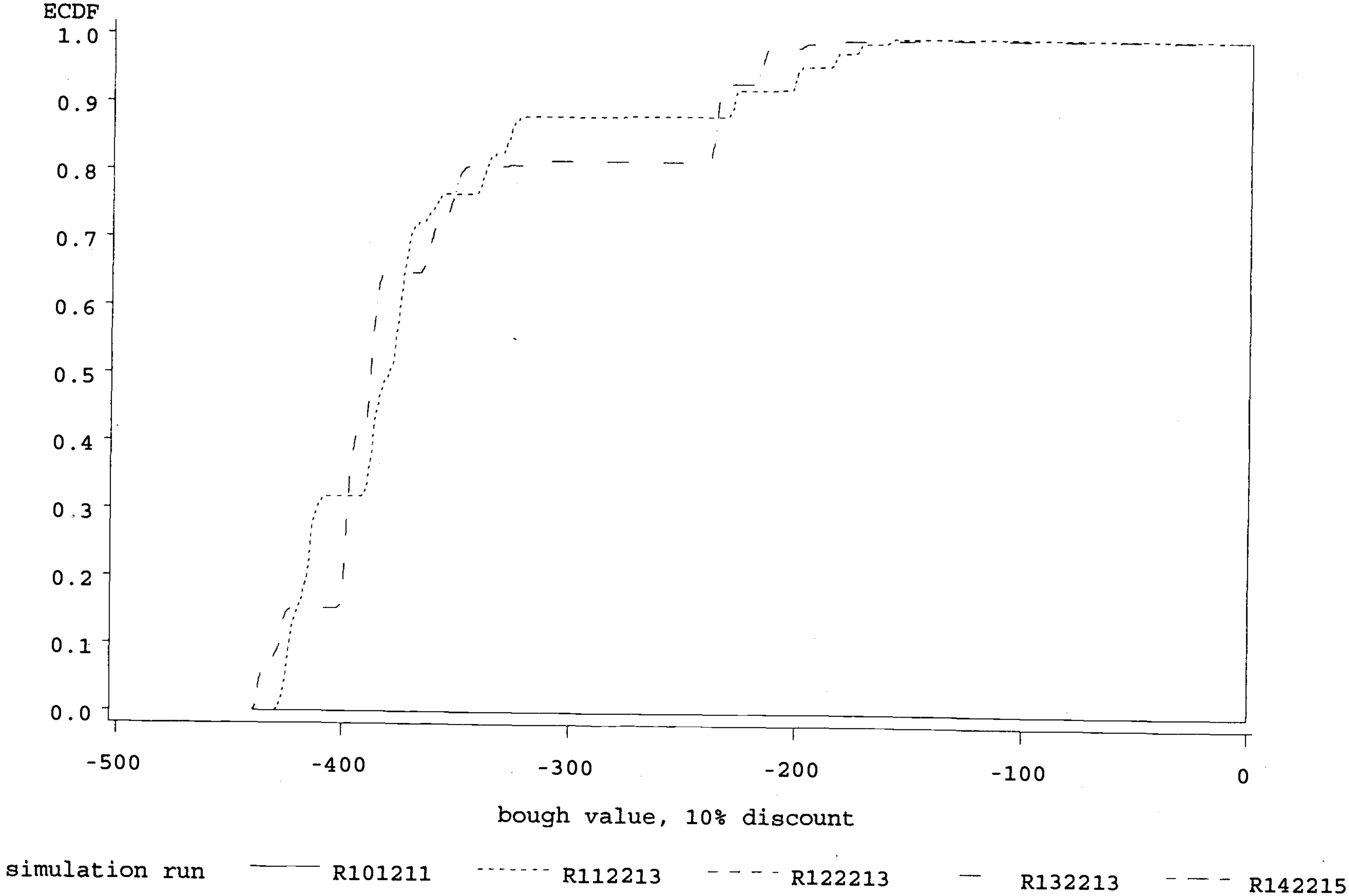

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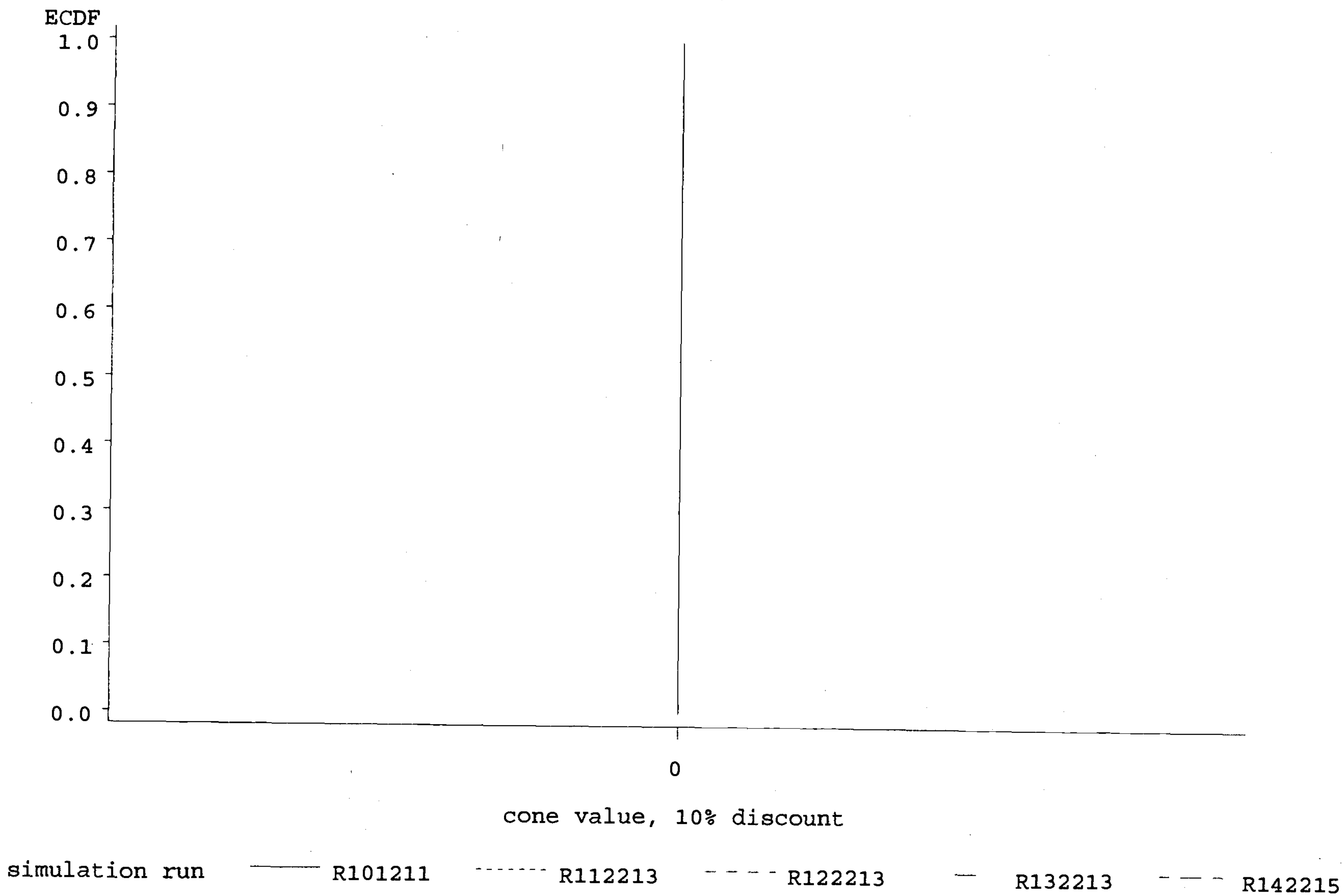
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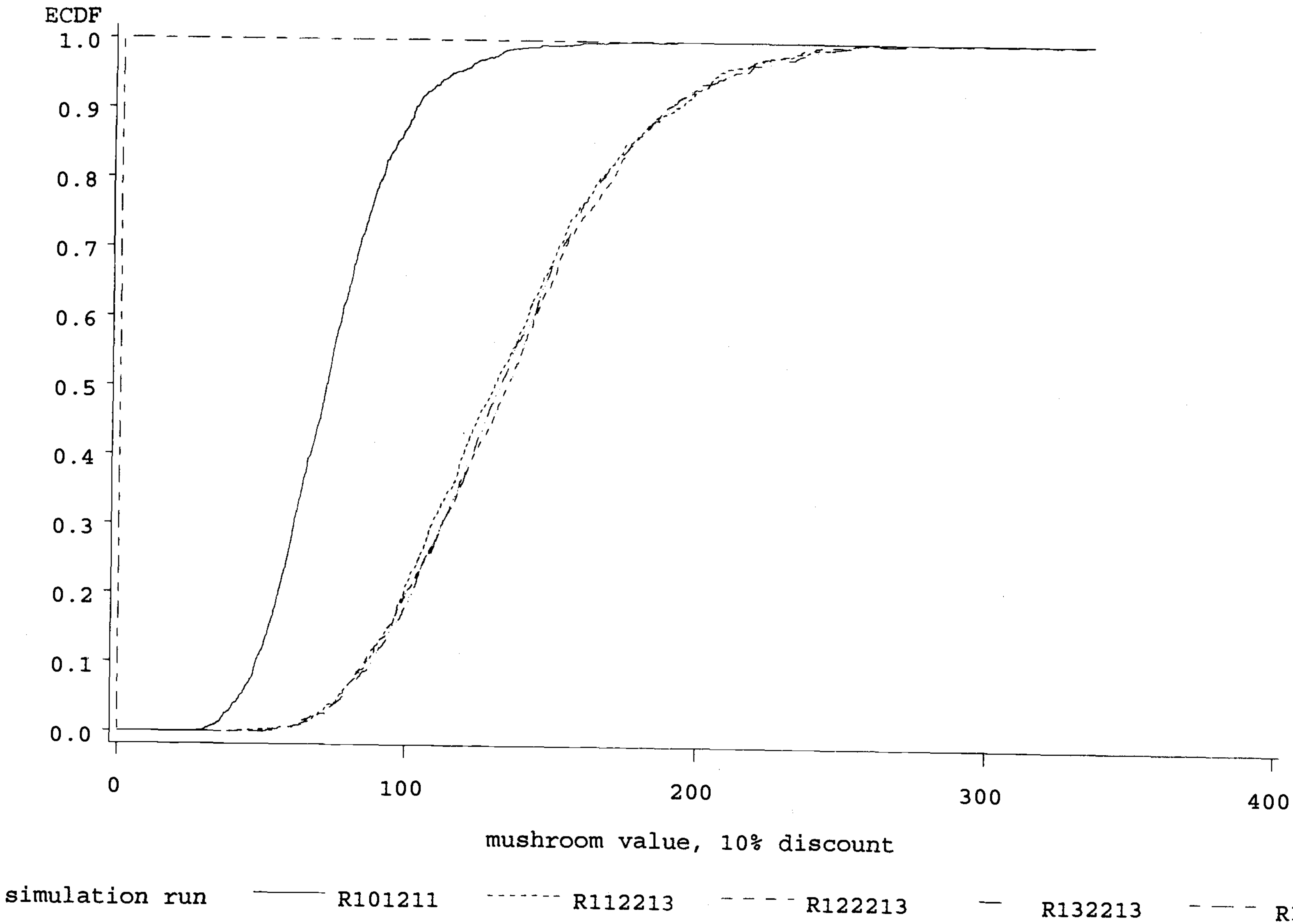
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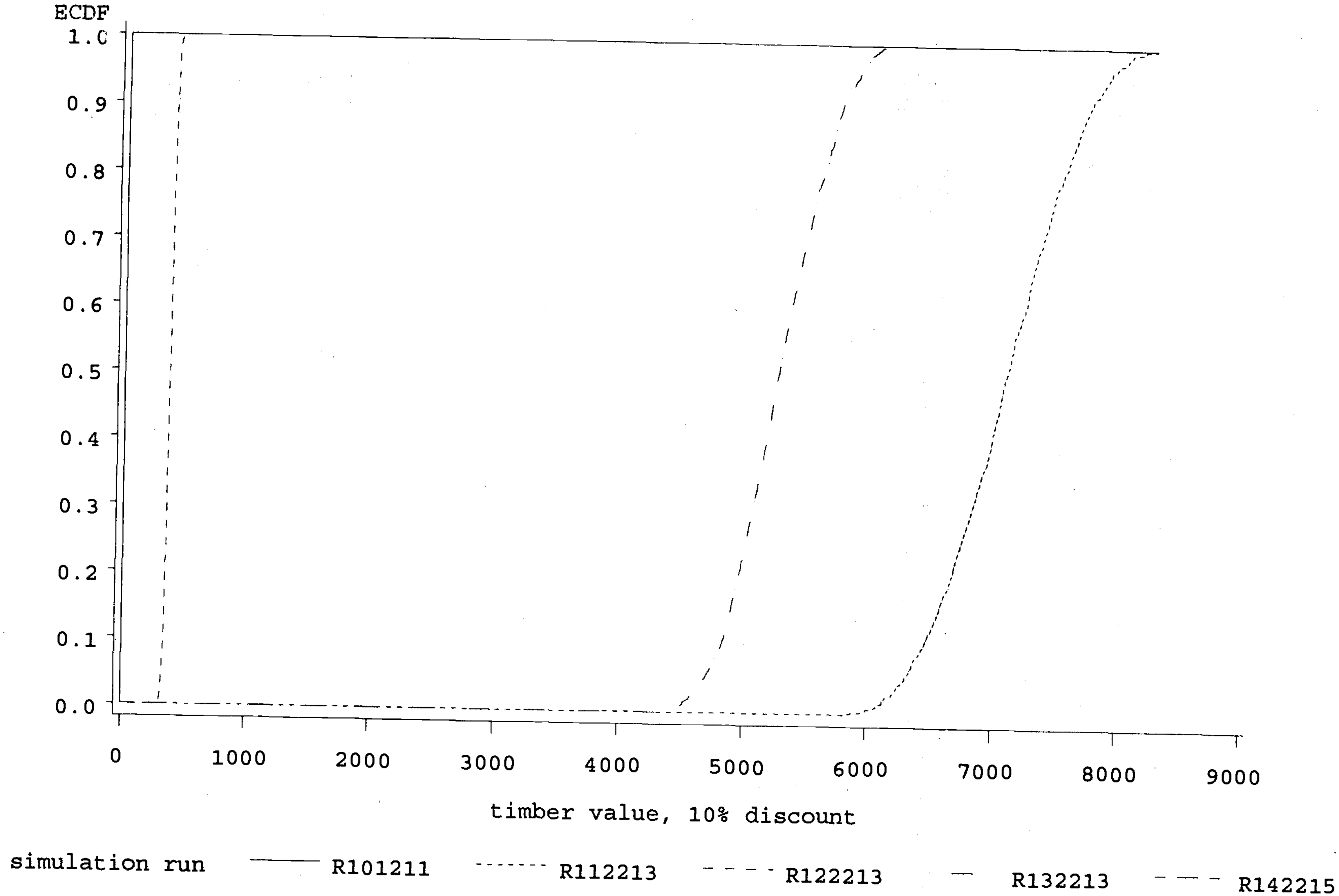
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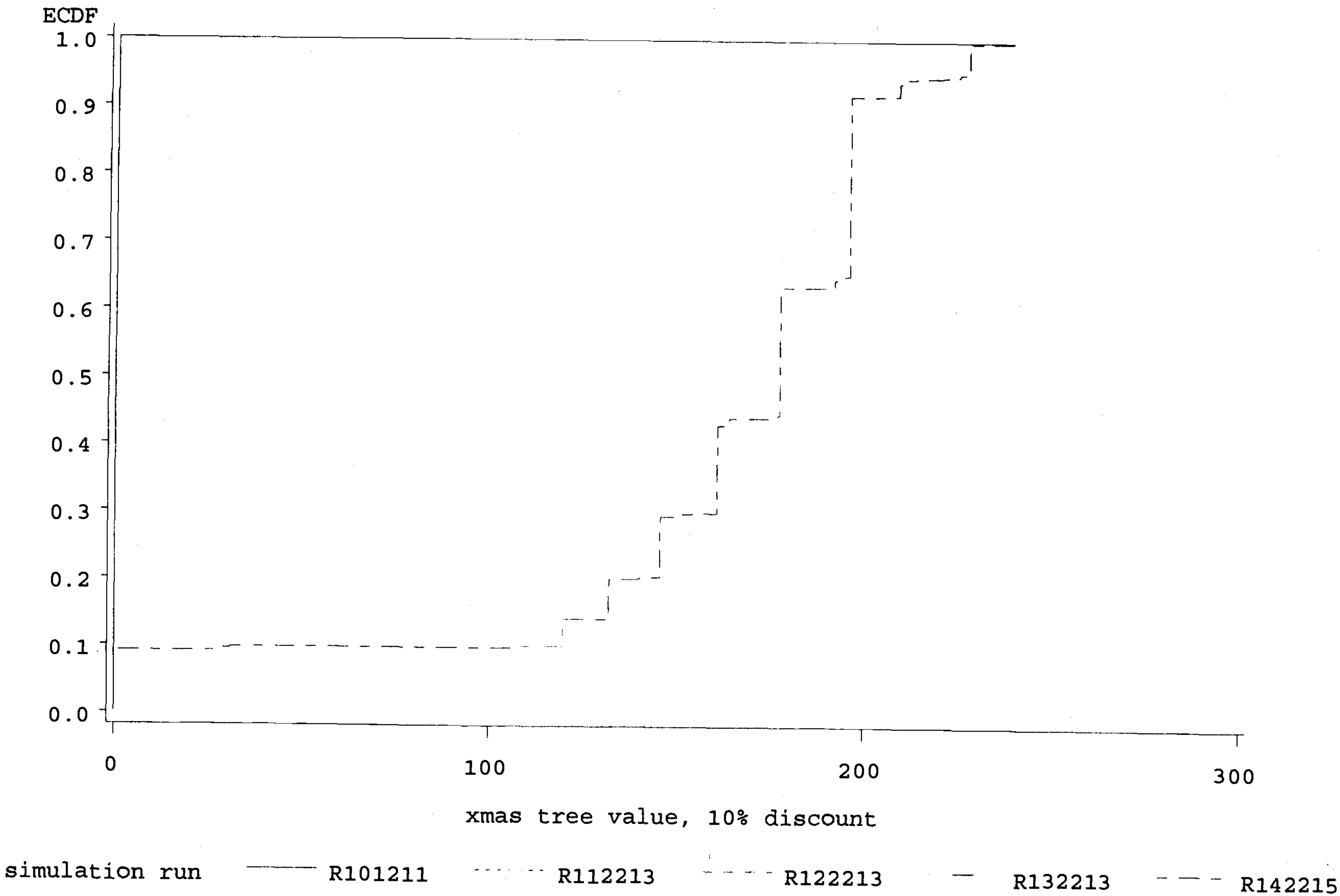

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7. Conclusion: Directions for New Research, Institutions, and Modeling Relating to Agroforestry with Pine Mushrooms in the Southern Cascade Range

Agroforestry requires shifting our thinking in both spatial and temporal domains, and demands skills in managing, rather than reducing complexity. Traditional disciplinary approaches to problem-solving such as the forester dealing with the trees, the soil scientist with the soil, and the hydrologist with the water, are no longer sufficient...Agroforestry challenges land managers to transcend disciplinary boundaries and explore the potential synergism between production agriculture and natural resource management.

Garrett and others (1994)

7.1. Introduction

Thus far, this thesis has assembled best available financial and ecosystem information, created a systems model to simulate future forest product prices and ecosystem processes, and conducted a policy analysis of options for forest management designed to culture pine mushroom in native forests. Integrating information from multiple disciplines has facilitated understanding about conditions conducive to developing and extracting commercial crops of pine mushrooms where pertinent information had previously been poorly organized or lacking. Chapters two and three described historic trends in pine mushroom and timber prices. Past prices furnish a basis for predicting future resource prices under different economic scenarios for the 25-year planning period from 1995 to 2020. Subsequent chapters developed a bioeconomic model that integrates economic and forest ecosystem processes affecting pine mushroom production (chapter four), stand management experiments designed to augment resource revenues and ecosystem knowledge about agroforestry systems that jointly produce pine mushrooms and timber (chapter five); and a policy analysis to reveal key issues of limitations, feasibility, and risks of proposed experimental agroforestry systems (chapter six).

The thesis is a first attempt to address managerial considerations for concerted management of pine mushroom management within the contexts of joint production and ecosystem management. Much work remains to be done to improve knowledge about ecosystem and economic processes affecting resource production as means to predict biological production and commercial yields. This final chapter addresses first the major directions in continuing research and modeling for pine mushroom agroforestry systems.

In addition, I suggest improved institutional arrangements for realizing hoped-for financial rewards from multi-product forest management.

Parallel challenges to develop agroforestry farming systems in other forest types with other non-timber forest products are apparent across North America. The process of inquiry and the prototype model developed here may serve as a generic template useful to developing other comparable systems in the region. Options for efficient technology transfer are discussed. While the main emphasis of this thesis has been a search to improve ecosystem management to increase production, a concurrent need for improvement in management of ecosystem information and models is implicit to this effort. Concluding remarks in this chapter reflect on considerations for streamlining computer-model building for greater ease in comprehension, application to other uses, and updating in an environment of continuous learning and model improvement.

7.2. Researching and Modeling the Effects of Water and Energy Flows as Mediated by Tree Canopy and Leaf Litter

Shaping forest vegetation to adjust the flows of water and energy reaching the soil surface has been the major goal in managing commercial Asian pine mushroom colonies in even-aged Japanese red pine stands. Proposed uneven-aged stand management at the Diamond Lake pine mushroom management area strives to create and extend indefinitely forest conditions comparable to those created for pine mushroom colonies found in even-aged commercial pine stands in Japan and Korea during mid-rotation decades. A key practice to producing favorable stand conditions is reducing the leaf area index by bough pruning, especially from that part of a tree canopy with the lowest photosynthetic efficiency, as a way to accelerate cycling processes in the forest stand. Side benefits to other forest resources are improvements in:

> *timber quality*, specifically for western white pine, the most valuable timber species in the Diamond Lake pine management area;
>
> *tree survival*, specifically for pine species, by reducing susceptibility to fungal infections; and
>
> *income from commercial bough harvests*, particularly from western white pine, Shasta red fir, and perhaps mountain hemlock, for which recent markets have developed (Gee 1995).

The principal aim of controlling leaf area index is to produce a subsoil environment favorable to the formation of mycorrhizae and nutrient exchange between host trees and pine mushrooms and to magnify pulses of water and periodic drops in soil temperature during the autumn fruiting season. A second way to reduce leaf area index is to thin stand trees for lumber production or for Christmas tree sales, particularly with Shasta red firs. Both Christmas tree and bough harvests provide intermittent incomes from uneven-aged forests (Gordon 1970), but planning and scheduling harvests remain an unperfected art.

Lack of explicit production functions, documented management trials, and directed market research will continue to stymie useful appraisals for financial feasibility of agroforestry in stand management. Without investment in these areas, underdevelopment of non-timber products will persist. Timing and flow of by-products from management to reduce leaf area index require more accurate prediction than are currently afforded in MUSHROOM. Product outputs and corresponding inputs of energy and water are not well-linked to tree growth. Data by which to predict commercial bough yields for the three commercial bough species, for example, do not exist. Likely production factors are tree dbh, tree height, previous pruning history, stand density, and branch growth responses to repeated partial pruning. Predictive production functions for commercial non-timber forest goods would function much as timber growth and yield models and in fact be closely linked to tree growth models. Hinesley and Snelling (1992) provide useful experimental designs for studying the efficacy of management practices in their study to develop regression equations to predict bough yields from Fraser fir (*Abies fraseri* (Pursh) Poir.) stands in North Carolina, for example. The authors observe that bough production succeeds best once tree reach three meters tall and following any Christmas tree harvests. Experimenting with harvest scheduling in MUSHROOM for bough pruning programmed in years after Christmas tree harvests conclude may reveal options for increased economic yields for the management trials proposed in chapter five.

MUSHROOM also hypothesizes that the organic litter layer is the second major filter for light and energy reaching the upper soil and pine mushroom mycelia. Japanese forest managers have for centuries actively removed branch debris and leaf litter from the forest floor where pine mushroom colonies flourish. In contrast, the naturally sparse understory vegetation at the Diamond Lake pine mushroom management area renders cutting and removing understory brush or raking the litter layer unnecessary in most instances. Soil samples taken in the vicinity of Diamond Lake show, however, that soil organic layers vary as a function of the dominant overstory species composition or other environmental features.

Important research tasks for improved modeling of the litter layer involve correlating differences in litter depth among species in response to topography, stand species composition, canopy cover, litter fall rates, and litter decay rates in high-elevations forests. Data on leaf litter for Shasta red fir and western white pine are wholly lacking, and comparative empirical data obtained locally for decay rates among species are not available for the five major tree species at Diamond Lake. Assumptions in

MUSHROOM about stands with more open canopies having faster litter decay rates and smaller net accumulations of litter must be demonstrated in situ. A better model for forecasting litter depth and soil environment in response to managing the forest overstory for improved pine mushroom production will first need extensive field data collection to calibrate model predictions.

7.3. Soil Environments and Modeling Pine Mushroom Productivity

Information and inventory analysis of soils where pine mushrooms occur in commercial quantities in the southern Cascade Range is limited. Soil scientists can contribute by correlating the flow rates of energy, water, and nutrients affecting pine mushroom reproduction to site-specific soil chemical and physical properties. Controlled studies could establish the conditions that bring about favorable soil environments for pine mushroom production. Then, management guidelines could be honed for achieving the soil organic layer depth that maximizes average annual production of pine mushrooms. Better characterization of soil environments where pine mushrooms are known to reproduce abundantly would also help managers choose sites where prospects for resource development are best. Major commercial harvests concentrate in forests where tree growth is comparatively slow and biological diversity and productivity in understories is low. To date, pine mushrooms reach greatest economic development in low-fertility, droughty sites such as sand dunes, volcanic ash and pumice soils, and eskers. These soil types and ecosystems, excluded from consideration for economic development in the past, may merit intensified management now.

Vogt and others (1982) have demonstrated the high diversity of mycorrhizal fungi species in Pacific silver fir stands of different ages growing on soils with thick organic layers. Depression of mycelial growth and fruiting from pine mushroom colonies under thick organic layers and the apparent absence of pine mushrooms from stands at Diamond Lake where Pacific silver fir predominates may indicate poor ability on the part of pine mushrooms to compete with other mycorrhizal fungi species present in soils rich in organic matter. More extreme soil environments typical of skeletal volcanic soils with little organic matter naturally and a shallow organic litter layer may depress the number of mycorrhizal fungi able to reproduce sexually and provide a functionally competitive advantage to pine mushrooms. Studies of the distribution of species diversity of mycorrhizal species are needed to understand resource partitioning and biochemistry affecting community ecology and reproduction of pine mushrooms and other mycorrhizal fungi.

Stronger pulses of water and solar energy resulting from a reduced organic litter layer and forest canopy may make the upper mineral soil environment even more extreme in an environment where nutrient limitations of volcanic soils already reduce species diversity and interspecific competition to benefit pine mushrooms. These assertions are hypotheses at present, but they are in concert with observations by mycologists in Japan and Korea studying the environmental conditions best suited to economic production of Asian pine mushrooms.

Principal among the unknowns is knowledge of how weather events trigger mechanisms controlling sporocarp fruiting of pine mushrooms. Further evidence is needed to predict fruiting accurately based on weather events at different temporal scales. The hypothetical model present in chapter four under the subprogram WEATHERDATA is crude and warrants a longer time series of pine mushroom monitoring to simulate response to weather. Unfortunately, organized data collection has thus far been irregular, limited to a few sites, and unfunded by any research institution. A challenge is finding the means to collect this information inexpensively in the face of reduced government agency research funding and the high cost of academic research.

The core of current ignorance is no clear understanding, and hence no definitive modeling capability, of the complex of responses in pine mushroom sporocarp production to the combined effects of soil type, weather patterns affecting energy and water inputs, and management practices to alter the forest canopy and ground litter depth, which mediate flows of gross energy and water inputs into the soil. Without institutional commitments to establishing experiments in the landscape and diligent monitoring in subsequent years, empirical data for describing and predicting production functions for pine mushrooms will not be forthcoming.

7.4. Links Among Cone Crops, Tree Growth, and Weather Patterns

Few forest scientists have equated cone production to tree growth and to weather events in a current or lagged year. Preliminary studies are available from Woodward and others (1994) for mountain hemlock and Eis (1976) for western white pine only. One limit to MUSHROOM is the absence of links between tree growth, tree reproduction, and nutrient availability as mediated by weather patterns. A tree-growth model based on historical weather data or a stochastic weather model would require considerable retooling. Commitment to time-series monitoring of the interactions between weather, tree stem and canopy growth, and cone production, however, would add to the explanatory power of the model and link cone production directly to other ecosystem processes in MUSHROOM. Predicting forthcoming lodgepole and western white pine cone crops would be helpful to managers in scheduling and maximizing harvest efforts, particularly when other forest products might be harvested at the same time.

7.5. Modeling Effects of Pruning on Tree Canopies and Tree Taper

Altering tree canopies through pruning raises issues central to stand modeling used for predicting wood biomass and product quality. Few data describe how canopies of trees change after bough pruning. Likewise, pruning creates knot-free wood and higher quality lumber. But, quantifying how pruning management translates into increased wood volume or quality premiums has not been described for the principle species in the Diamond Lake pine mushroom management area. An important unknown result of tree pruning is the effect of tree taper. Even if total bole wood volume does not increase from pruning, the actual volume of dimension lumber may increase because reduction in taper may increase length of lumber pieces. These production relations figure importantly in planning for eventual economic yields from western white pine management where the species is being reintroduced.

Existing allometric equations used to measure tree canopy volume and mass are based on tree dbh or tree height, but canopy volume and mass may be less correlated with tree dbh or tree height after pruning. Empirically-based, species-specific algorithms to express how a tree canopy width and biomass change in years after pruning management are not yet available. Current calculations of canopy biomass and leaf area from equations used in the current version of MUSHROOM are not likely to produce accurate estimates of interceptions of water and solar energy by pruned canopies. Better modeling of managed tree canopies is needed. Geometric models of tree crowns in three dimensions for both pruned and unpruned would be a welcome improvement.

7.6. Improving Models for Natural Mortality and Regeneration of Trees

MUSHROOM currently does not account for fire and treefall disturbances, that is, causes of tree mortality other than density-dependent mortality. Particularly in stands dominated by mountain hemlock, laminated root rot (*Phellinus weirii* (Murr.) Gilb.) causes frequent cohort fall down and small canopy gaps (Cromack and others 1991, Thies and Sturrock 1995). Stochastic models to predict the initiation, rate of spread, and resulting tree mortality of the root rot on mountain hemlock and Pacific silver fir would add to the veracity of stand simulations. Recent studies of fire frequency and intensity in red fir forests in the southern Cascade Range (Taylor 1993) can provide a starting point for modeling stochastic mortality as a function of fire frequency and intensity and subsequent stand development.

The model for predicting gap regeneration can benefit especially from recently published studies. Data on post-fire regeneration of Shasta red fir, lodgepole pine, western white pine, and mountain hemlock from nearby Crater Lake National Park (Chappell and Agee 1996) and on regeneration in artificially created gaps seeded with Pacific silver fir from the central Oregon Cascades (Gray and Spies 1996) offer empirical data to improve simulation of species-specific regeneration responses in gaps as a function of gap size and origin. Linking young-tree growth, cone crop size, availability of gap spaces, and the most recent gap-disturbance event in stands will improve stochastic modeling of regeneration.

7.7. Interdisciplinary Research for Joint Production

Research on ecological and economic processes in forest management presents uncomfortable challenges. Inquiry into the facets of forest science just discussed would do much to improve the quality of a stand-level joint production needed to model agroforestry production. Progress in modeling joint production has been slow to take hold in contrast to individual resource (and primarily timber) production. Disincentives to engage in multidisciplinary research continue to impede. Traditional specialization in one discipline discourages tackling broad-scale, complex issues in ecosystem management, and academic or research careers are seldom founded on interdisciplinary studies. Start-up time, intensified need for communication among already busy people, and bureaucratic procedures thwart rapid progress in collective efforts.

Attempts to bring together academic researchers, public agency researchers, and land management staffs for management with experimentation as exemplified in the Demonstration of Ecological Management Opportunities (D.E.M.O.) Project are rare. Logistical concerns, procedural requirements for cutting trees on public lands, and short field seasons test people's dedication to interdisciplinary work. The Project, which has funded the work in this thesis, evolved through Congressional fiat rather than institutional commitment by the U.S.D.A. Forest Service to interdisciplinary work that addresses thorny problems in ecosystem management. While researchers from public land management agencies understand the need for interdisciplinary research, research agendas and funding allocations frequently fail to reflect and promote interdisciplinary work. Budgeting according to multidisciplinary management research topics, e.g. pine mushroom management, rather than according to academic disciplines breaks down traditional disciplinary isolation and reductionism. If budgeting does not reflect projects, interdisciplinary work is hampered by insufficient commitment.

7.8. Searching for Expertise

Lack of institutional expertise and capacity on the part of Federal land management to respond to persistent questions about means to manage pine mushrooms spurred development of this prototype model. Developing the model MUSHROOM and using the model for policy analysis has been one way to generate information about agroforestry joint production, its applicability in specific forest ecosystems, and research needs to cover present gaps in knowledge. Generating a prototype model as a tool for decision support by integrating disparate information synthesizes and integrates knowledge to create a model that functions as an "expert." The model can focus efforts to improve understanding and research efforts including management experiments.

Management experiments provide opportunities for faster learning about variation in ecosystem responses to applied management than does passive observational monitoring (Walters 1986). Here, I have proposed that a close look at forest conditions and practices that support commercial production of Asian pine mushrooms can provide direction to experimental management for North American pine mushrooms. Further international outreach can help accelerate design in management experiments of the kind described in chapter five. Hosford and Ohara (1995) furnish the only example thus far of joint Japanese-North American efforts to study the life history of the North American pine mushroom and to apply the traditional knowledge of Japanese forest science to expand knowledge of the North American pine mushroom. Forest scientists studying North American pine mushrooms have as yet little contact with forest managers and scientists in Korea, where most pine mushrooms have been produced in the last two decades.

North Americans have rich sources of neglected expertise among their own population that can complement expertise acquired from life history studies and experimental data. One source is the community of long-time Japanese-American pine mushrooms pickers. Time-series data already exists in the memories of Japanese-Americans, many of whom grew up in rural Japanese cultures and have continued to gather pine mushrooms in the Pacific Northwest in a manner scarcely possible in contemporary Japan. People with rural backgrounds in Japan and subsequently transplanted to the Pacific Northwest have observational knowledge that, if collected, can guide managers and scientists in understanding the relations between forest community structure, physical terrain features, and weather events on the one hand and the production of pine mushrooms. Another set of time-series observations comes from Native peoples whom anthropologists have reported collecting and eating North American pine mushroom. Detailed documentation of gathering strategies, information on sites with high probability of high productivity, or descriptions of indigenous management are missing altogether.

Recognizing the worth of information from people without high professional status or formal training in scientific methods may be unusual and uncomfortable for forest science and management institutions in North America. But, soliciting community participation and analyzing ecosystem knowledge of non-scientists are common practices in rural development in tropical ecosystems, and particularly in development of agroforestry systems to improve production (Walker and others 1995). In the Pacific Northwest, time-series information from expert pickers may disappear forever as long-time pickers pass away and traditional venues for receiving oral history about gathering traditions are lost. Capturing this set of time-series observations by interviewing long-time pickers needs to be a high priority for social science research.

Table 7.1. evaluates the status of knowledge about the various products. The status of knowledge is deficient for most non-timber products. New information is inevitably needed as previous research or cultural anthropology studies cannot be expected to address all current and future resource management questions. With high administrative overhead and low research funding in the foreseeable future, land management agencies need to develop cost-effective methods to gather data. An expert workforce to carry out stand tending and forest ecosystem monitoring outlined in proposed ecosystem management experiments in chapter five will need to be found. Labor needs to meet commitments to ecosystem management in the face of reduced funding may spur particular innovation in both Federal land management and ecosystem research.

Table 7.1. The comparative status of knowledge about the pricing and production of forest products from the Diamond Lake pine management area.

Resource	Pricing and Market Information	Production Functions
timber	good	good
Christmas trees	good	good
cones	poor	fair
conifer boughs	fair	poor
medicinal / edible plants (e.g. *Chimaphila* spp.)	poor	none
pine mushrooms	fair	poor

Long-term stewardship contracts may be a significant source of labor to accomplish the fine-grain vegetation management for propagating and harvesting non-timber forest products while Forest Service personnel continues with coarser-grain management of timber products. Finer-scale stand tending would contribute, for example, to ongoing management experiments to study microsite effects on pine mushroom productivity and effects of harvesting other forest products on the sustainability of pine mushroom resources. Such stand tending is currently beyond the reduced labor force capacity of the National Forest Service. Stewardship contracts may be one solution to conserve and advance site-specific ecosystem knowledge among local residents and provide additional employment from commodity-based ecosystem management. Local stewards would earn income from harvests of non-timber forest products over designated portions of special management area such as the Diamond Lake pine mushroom management area in exchange for custodial management that serves ecosystem productivity and economic production.

Considerable risk to the financial security of the steward arises from current uncertainty about the timing and quantity of commercial crops. The low aboveground biological productivity in the Diamond Lake pine mushroom management area may entail comparatively long intervals between years with commercial harvests of a non-timber forest product. Large stewardship tracts might be necessary to sustain financially even a single steward. The rural stewardship labor force might have additional employment by participating in monitoring and data collection programs that carry out the mission of adaptive learning in conjunction with ecosystem management. Training as ecosystem technicians offers rural residents diversified opportunities to carry out ongoing ecosystem monitoring and experiments that accelerate ecosystem learning and economic development.

Local, non-traditional ecosystem-based research organizations, operating with reduced overhead costs, may develop a competitive lead in contracting to oversee research about ecosystem management (pine mushroom agroforestry) and ecosystem processes (pine mushroom / tree host ecology). Rural-based research organizations such as the Rogue Institute of Ecology and Economics in Ashland, OR, and Klamath GIS in Hayfork, CA, already function in these roles and have provided seminal efforts (Everson and Gremaud 1995, Everett 1996) in rural labor training to meet the research and monitoring needs occasioned by intensified stewardship of agroforestry ecosystems in the axis region of the Cascade, Siskiyou, and Klamath mountains in the Pacific Northwest.

7.9. Technical Improvements in Model Structure and Development

Effort required to create a computer model to simulate ecological and economic processes of agroforestry systems is wasted if the model has no intended audience. Modeling then becomes an academic exercise without responsibility to real-world needs of ecosystem management. MUSHROOM contains several flaws in this respect if there is no follow-up going beyond the academic scope of this thesis. First, the potential users of this model confined presently to the few people involved in pine management in the Diamond Lake pine mushroom management area or at similar sites close by. Secondly, there is no institution established in land management agencies or universities to improve and expand the usefulness of the model to other ecosystems or to other agroforestry systems.

In tandem with efforts to acquire ecosystem knowledge continuously from managerial monitoring and experimentation with pine mushroom culture, the need to make continuous improvements in models for decision-support is equally urgent. Absence of infrastructure for model custodianship and maintenance condemns models to rapid obscurity and irrelevance. Developing and maintaining agroforestry models and expanding their scope by linking them to tree-growth models cannot proceed in a socially useful way without consistently funded institutions charged with maintaining ecosystem and bioeconomic models in a manner parallel to database management.

Model conservation and maintenance incurs development costs for improving models and expanding their utility, but these systems costs weigh in against the costs of inefficiencies in model building when models must be built from scratch because data links and communications among institutions and scientists are poorly developed and maintained. There is a need for research institutions to invest in directed model construction and maintenance as much as in data collection. Models serves as references to guide research direction and illustrate purposeful research synthesis to decision-makers allocating research funds. Likewise, models conserve hypotheses and document current thinking about topics in ecosystem science for which adequate information is not yet available.

The present model responds to essentially economic concerns of forest management, in particular how to culture an economically significant native mycorrhizal mushroom species for greater yield. The specific instance of one species, pine mushrooms, at one locale, the Diamond Lake pine mushroom management area, limits the immediate relevance of the model. For this reason, MUSHROOM is only a prototype management model. More helpful to scientific and managerial understanding would be development of a generalized ecosystem process model (Reynolds and Acock 1997). Such a generic model would allow for incorporating a greater or smaller number of species, different types of forest products from different agroforestry systems, a range of ecosystems, and different planning intervals into the model, beyond the present scope of MUSHROOM. Tailoring a generic model to a wide variety of ecosystem situations involving joint production agroforestry systems would educate and inform more widely and provide more feedback from users to model developers and custodians. Modularity and portability of individual biological or economic-decision modules from a successor model to the MUSHROOM prototype can furnish a library of functions for appropriate eclectic use by managers or researchers focused on site-specific managerial topics for agroforestry in particular ecosystems.

Certain practices may also ensure greater usefulness of similar bioeconomic agroforestry models. An esssential change involves eventual replacement of empirical functions with explanatory process models where possible. Substitution of the FVS-based model by a tree-growth model using existing models of weather, soil, and disturbance processes would give greater realism to projection functions of annual crops such as mushroom and cones. Improvements in code writing are also needed so that changes in ecosystem details, species composition, and principal products engender minimal program rewriting. To date, most process-based vegetation models have described monocultural row crops or plantation forestry. Spatially-heterogeneous, species-rich, and uneven-aged forests demand a greater complexity of process interactions than crop models. Field data upon which to base process outcomes may require consider time to collect and evolution of a purely process-based model may require considerable time.

Economic processes that determine product prices of agroforestry goods occur at geographic market scales larger than stands, watersheds, or landscapes used for bioeconomic agroforestry models. Continually updated global or national economic models projecting product prices that bear on local managerial decisions in smaller-scale forest ecosystems need better links to local users. One useful network link would be between latest price projections produced from TAMM, the U.S.D.A. Forest Service timber supply model, and local agroforestry production models. A similar global model for projecting pine mushroom prices could update price information or price forecasts in the bioeconomic model with each new projection. The importance of making multiple price projections under different combinations of assumptions would remain an important tool for decision-makers by providing a sense of the range of possible outcomes under plausible assumptions about the future.

Lastly, a program language other than QBasic may improve the run-time performance, effective modular portability, and intelligibility of the computer code. Object-oriented programming may achieve desirable comprehension for both lay person and technical expert interested in the model structure. Also, the choice of language may assist in speeding up the cycle of model maintenance, revision, updating, and data transfer (Sequiera and others 1997) once the model is embedded in a custodial infrastructure. Within the program structure of MUSHROOM or a successor model, elements for improvement include: reducing the transfer of data across subprograms, particularly with the price and volume calculations for lumber; and reducing the number of global variables.

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