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Management Experiments for High-Elevation Agroforestry Systems Jointly Producing Matsutake Mushrooms and High-Quality Timber in the Cascade Range of Southern Oregon

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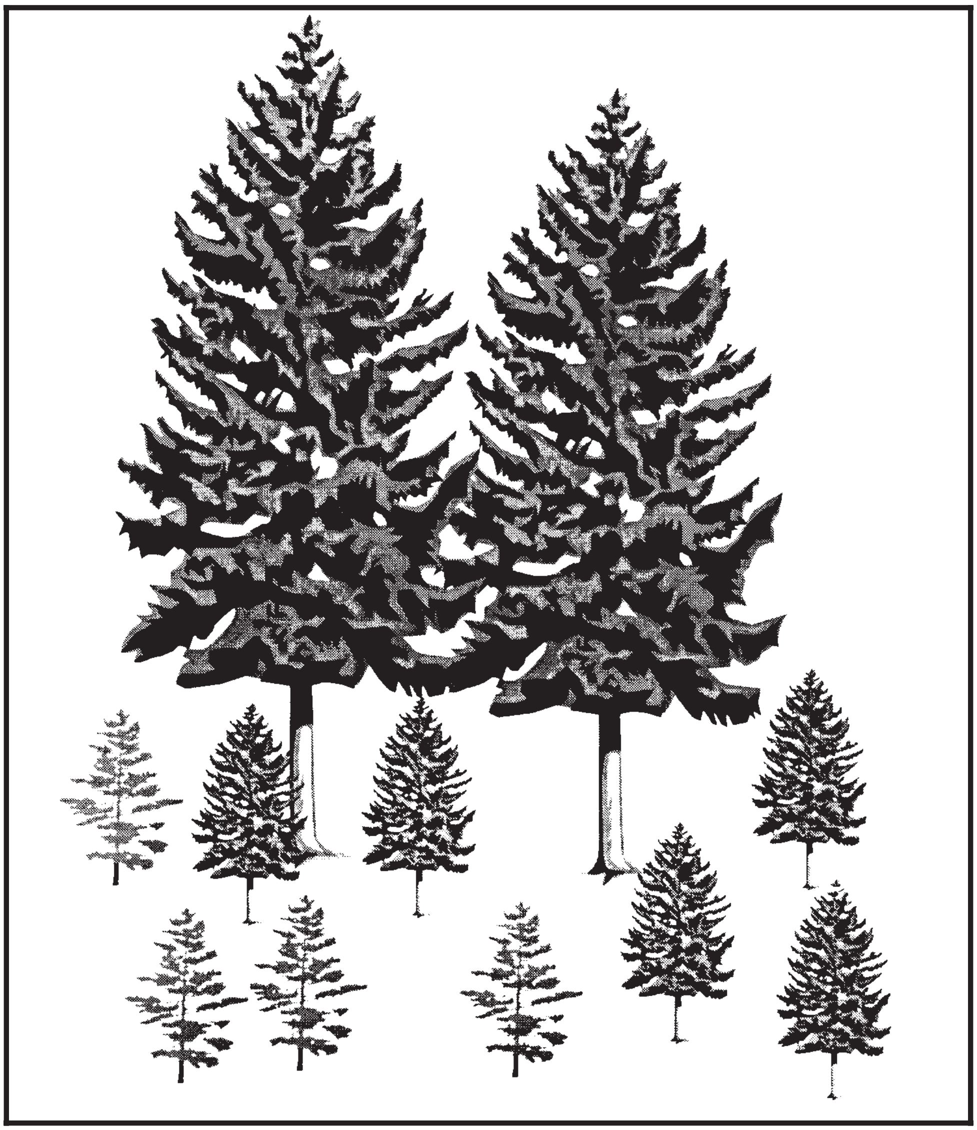

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Abstract

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Experimental prescriptions compare agroforestry systems designed to increase financial returns from high-elevation stands in the southern Oregon Cascade Range. The prescriptions emphasize alternative approaches for joint production of North American matsutake mushrooms (also known as North American pine mushrooms; *Tricholoma magnivelare*) and high-quality timber. Other agroforestry byproducts 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 matsutake reproduction. Programs of thinning and branch pruning test regulating flows of energy and moisture to mushroom mycelia in the upper soil. Experimental prescriptions incorporate monitoring to evaluate ecosystem responses to management and to accelerate adaptive learning.

Key words: *Tricholoma magnivelare*, agroforestry systems, nontimber forest products, adaptive management, *Abies magnifica*, *Tsuga mertensiana*, *Pinus contorta*, *Pinus monticola*, *Abies amabilis*, tree pruning.

Contents

Introduction

Growth in the international trade in North American matsutake mushrooms (*Tricholoma magnivelare* (Peck) Redhead) from forests in the Pacific Northwest to markets in Japan (Weigand 1997) has prompted forest managers to consider silvicultural practices that increase commercial production of matsutake 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 matsutake mushroom production is the absence of a tradition of matsutake mushroom management in North America. By contrast, matsutake mushrooms of the closely related species *T. matsutake* have been managed for centuries in eastern Asia (Hosford and others 1997, Totman 1989). Agroforestry technology developed for matsutake mushroom culture in Japanese, Korean, and Chinese forests may be useful in several North American forest types, particularly forests comprised of lodgepole pine (*Pinus contorta* Dougl. ex Loud.; Pilz and others 1996b), jack pine (*P. banksiana* Lamb.; Miron 1994), and ocote pine (*P. ocote;* Villarreal 1993).

A network of matsutake mushroom management areas has been established in Washington and Oregon to study the ecology and productivity of matsutake mushrooms (Hosford and others 1997). Sites represent a broad spectrum of habitats from sea level to 1800 meters in elevation. Wide distribution over many climate and vegetation zones suggests that matsutake mushrooms may have evolved different physiological responses to local conditions. An important zone of high natural productivity and concentrated commercial harvest of matsutake mushrooms straddles high-elevation forests on both east and west slopes of the Cascade Range in southern 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 matsutake mushrooms, however, remains fragmentary.

This report focuses on incorporating experimental design into stand prescriptions that combine timber management and matsutake mushroom culture. Designing easy-to-execute experiments within management activities can test means to increase commercial harvests of matsutake mushrooms and provide new information about matsutake mushroom management. Traditional management for matsutake mushrooms in eastern Asia is best suited to low-elevation, single-species, even-aged stands receiving summer rain. Uncertainty about appropriate management for matsutake mushrooms in high-elevation, multispecies, uneven-aged stands in the Cascade Range underscores the need for experimental prescriptions designed to clarify direction in matsutake mushroom management. Risk to net economic yields of forest products from innovation may be alleviated by concurrently managing timber resources for improved tree vigor and timber quality. Examples here illustrate potential experimental management at the Diamond Lake matsutake mushroom management area in the Umpqua National Forest, Douglas County, Oregon.

Physical Environment

Location and Topography

The Diamond Lake matsutake mushroom management area is 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 kilometers northwest of the north end of Diamond Lake. Elevation ranges from 1675 to 1750 meters. Slopes within the management area range from flat to 23 percent. Aspect is from northwest to east. The site is shielded from prevailing southwest winds and resulting windthrow, a prominent phenomenon at other productive matsutake mushroom sites nearby.

Soils

The management area is northwest of the Crater Lake caldera in a zone of thick deposits of volcanic ejecta from the explosion of Mount Mazama 7,000 years ago (Carlson 1979). Other volcanos in the immediate vicinity are Mount Thielsen (2780 meters) and Mount Bailey (2550 meters). 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 centimeters 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 and others 1981, Shoji and others 1993) and elsewhere in the southern Cascade Range (Alexander and others 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 gram per cubic centimeter 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 spring (Cochran and others 1967). Average summer temperature of soils in the area is 14 °C (Kimble 1993).

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 millimeters.

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, 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 (*A. concolor* (Gord. & Glend.) Lindl.) occur sparsely. Of the major species, Pacific silver fir and western white pine appear not to form mycorrhizae with matsutake mushrooms in the management area.

The dominant plant association type (Atzet and others 1996) is mountain hemlock/grouse whortleberry (*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 percentage of cover by understory vegetation. Prominent nontree species in the understory and in gaps include pinemat manzanita (*Arctostaphylos nevadensis* Gray), golden chinkapin (*Castanopsis chrysophylla* (Dougl.) A. DC var. *minor* (Benth.) A.DC.), squawcarpet (*Ceanothus prostratus* Benth.), pipsissewa or prince's pine (*Chimaphila umbellata* (L.) Bart.), and little prince's pine (*C. menziesii* (R. Br. ex D. Don) Spreng). A list of 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 8 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 40 or more years old.

Key Management Concerns

Few silviculturists have attempted intensive management for timber production at high-elevation sites in the zone of Mount 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 precommercial 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 combining matsutake mushrooms and timber.

Grier and others (1989) point out that investments in forest stands should not be based solely on net primary aboveground productivity. Sites yielding products with disproportionately high economic value per unit of biomass may in the long run be advantageous to manage, and may garner broad 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 stand scale. 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 an array of valuable crops, such as high-quality western white pine timber and matsutake mushrooms, with long histories of consumer demand globally, cushions uncertainty about future markets and management costs.

Management for matsutake 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 matsutake mushrooms fail to hold up in practice. Failure-resistent 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 matsutake 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. Small-scale disturbances also are 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 in depth here, 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). Multiproduct management described here is more labor intensive than traditional timber-based extraction. Improved links between nontraditional 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 nontimber forest products (Mater Engineering, Ltd. 1992). Without a secure forest-based labor force and organized networks to distribute nontimber 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 forest products. These values are not explicitly included here as outputs; instead, amenity values function as constraints to management. In some cases, management for a commercial resource ensures that one or more amenity values are preserved. For example, management concerns for aesthetics and adequate tree regeneration coincide. Favoring partial cutting with considerable overstory retention maintains old-growth trees and old-growth-dependent species and creates a visually diverse landscape. Current work underway near the Diamond Lake matsutake mushroom management area will describe in detail public responses to the aesthetics of partial overstory retention.[1]

All tree species found originally in the stands before management are retained to some degree in managed stands under the assumption that total biological diversity is therefore conserved at the stand level. Biological diversity at higher geographical orders likewise constrains management in terms of wildlife corridors and large-scale wildlife habitat needs. Specific constraints tied to adjacency and landscape connectivity are not specifically addressed here.

Management Experiments

A range of stand prescriptions described here implements agroforestry systems that jointly produce timber, matsutake mushrooms, decorative boughs, Christmas trees, and pine cones. The prescriptions elaborated here have not yet been implemented on the ground; Weigand (1997) developed them in consultation with Umpqua National Forest staff for computer modeling of the production and value of multiple forest products, both timber and nontimber, over 25 years. Table 1 gives an overview of major timber and nontimber products currently or potentially available in the Diamond Lake matsutake mushroom management area. Each prescription tests the feasibility of one or more management options as tools for overcoming barriers to investment in high-elevation stands for cropping nontimber products listed in table 1. Harvests of one or more nontimber products early in the cutting cycles in an uneven-age management regime may generate sufficient income to finance costs for augmenting stand productivity. Monitoring these interventions will help evaluate whether agroforestry management practices leave stand structures and ecosystem processes intact and produce expected results.

Management with a multiproduct approach emphasizes product quality for timber produced in small quantities at long intervals. 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.

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[1] Ribe, Robert G. 1994. Critical public perceptions of alternative forest managements in the Cascade Range of the Pacific Northwest: demonstration of ecosystem management options, social perceptions study component, study plan proposal. Unpublished manuscript. 27 p. On file with: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Forest Sciences Laboratory, P.O. Box 3890, Portland, OR 97208-3890.

Table 1—Potential agroforestry products from the Diamond Lake matsutake mushroom management area, Diamond Lake Ranger District, Umpqua National Forest, Oregon

Product category and product	Estimated price per unprocessed unit	Source
	1990 U.S. dollars	
Foods and flavorings:		
Tricholoma magnivelare	22.00/kg	Amaranthus[a]
Chimaphila umbellata, Chimaphila menziesii	4.18/kg	Miller 1988
Decorative cones:		
Pinus contorta	.75/kg	Thomas and Schumann 1993
Pinus monticola	1.33/kg	Thomas and Schumann 1993
Decorative boughs:		
Abies amabilis (open-grown)	.35/kg	Schlosser and Blatner 1996
Abies magnifica	.35/kg	
Pinus contorta	0-.20/kg	
Pinus monticola	.25/kg	
Tsuga mertensiana	0-.25/kg	
Christmas trees:		
Abies amabilis (open-grown)	1.82 per tree	USDA Forest Service 1996
Abies magnifica	1.82 per tree	
Wood products:		
Abies amabilis	230.08/mbf[b]	USDA Forest Service 1996
Abies magnifica	205.25/mbf[b]	
Pinus contorta	88.01/mbf[b]	
Pinus monticola	299.45/mbf[b]	
Tsuga mertensiana	234.64/mbf[b]	

[a] Personal communication. 1997. Michael Amaranthus, research forester, formerly with the Pacific Northwest Research Station.
[b] mbf = thousand board feet.

Effects of forest management practices on North American matsutake mushrooms are poorly known. Most information about responses by matsutake mushrooms to changing forest production 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 matsutake 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 matsutake 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 matsutake 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 matsutake mushrooms in the Diamond Lake area as compared to dry southwest slopes in Japan and Korea (Hosford and others 1997, Lee 1983). 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 owing to the naturally sparse understory. Other environmental effects, such as fire frequency, are of greater concern in the Cascade Range but not significant in the wet summer climate of Japan.

The tradition of matsutake mushroom management in eastern Asia serves as a point of departure from which to synthesize and test hypotheses about promising options for managing North American matsutake mushrooms. Basic differences in climate, soils, and tree species, however, point to the need to manage for matsutake mushrooms in commercial timber forests with objectives, goals, and practices adapted to local site conditions.

Management Objectives and Goals

Management for matsutake 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
- to expand suitable habitat for matsutake 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 matsutake mushroom management area were 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 will alter management for North American matsutake mushrooms in response to economic signals and technological advances. One hypothetical example of an adaptive change in matsutake mushroom management might involve efforts to regenerate Pacific silver fir were new evidence to show that it is a matsutake mushroom host species and that it creates suitable forest environments for commercial quantities of matsutake mushrooms. Potential advances in culturing Asian matsutake mushrooms under intensive domestication, on the other hand, might reduce demand for North American matsutake mushrooms in Japan, the major consumer market.

Experimental Treatment Strategies

Five strategies, described briefly in the following paragraphs, 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
- thin and prune trees to concentrate nutrients and organic matter on fewer trees
- harvest nontimber products when commercial quantities are available

Adhere to Societal and Ecological Constraints

Management scenarios proposed here assume that society's interests in public forests are best served 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 is entirely eliminated from the stand. Shifts in species dominance are, however, planned as part of efforts to reduce tree pathogens and improve the quality and quantity of economic production. The focus of regeneration is management of gaps of 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.

Reduce Tree Pathogens

Inventory records from the Diamond Lake Ranger District showed multiple widespread tree pathogens in the matsutake 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 matsutake mushroom production by supplying more fine root sites for mycorrhizae-mediated carbohydrate supplies to matsutake 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 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[2] (Hawksworth and Wiens 1996).

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[2] Personal conversation, Norman Michaels, silviculturist, U.S. Department of Agriculture, Umpqua National Forest, Diamond Lake Ranger District, Diamond Lake, Oregon.

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 matsutake 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 5 to 10 years after opening gaps in the forest. Vector trees for mistletoe infestations, particularly from the control plots, are kept at least 20 meters 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 (Hoff 1992, Snellgrove and Cahill 1980). 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 (1995) 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 1995, Lishman 1995).

Reduce Pacific Silver Fir and Increase 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 1). Its clustered foliage and comparatively low leaf area of individual 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 matsutake mushrooms may reduce or delay water and energy transfers necessary to induce matsutake mushroom growth and reproduction.

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 matsutake mushroom fruiting. Thinning trees and pruning branches both reduce leaf area index, although the intensity of control differs with each practice. Thinning reduces drought stress and concentrates biomass on trees having the best prospects for financial returns or on trees promoting the best environment for matsutake mushrooms. Wood quality of pine species, in particular, improves and tree taper is reduced (O’Hara and others 1995b). Pruning to the height of the first merchantable log (5.3 meters) 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 true fir and hemlock species for wood quality in the Pacific Northwest. An additional topic for original management experiments would be to overlay pruning and nonpruning treatments to randomly selected management circles in the matsutake mushroom management area. General pruning guidelines are presented in the following tabulation. Pruning of 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.

	Pruning guidelines	
Species	Height class	Pruning height
	Meters	
For all trees species, except pines:	>5.0	2.5
	>13.0	5.3
For western white pine:	>2.5	1.2
	>5.0	2.5
	>13.0	5.3

For lodgepole pines in a stand where they comprise more than 60 percent of stand basal area:

Prune as for nonpine species.

For lodgepole pines in a stand where they comprise less than 60 percent of stand basal area:

Prune only if trees have a crown ratio greater than 75 percent.

	Height class	Pruning height
	>4.8	1.2
	>10.0	2.5
	>20.0	5.3

Sources: Hungerford and others 1982; O'Hara 1995a, 1995b; Russell 1995.

Harvest Nontimber Forest Products Opportunistically

Harvests of nontimber forest products, including boughs, Christmas trees, and pine cones in addition to matsutake 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 1997). 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 of open-grown true firs per hectare with diameters at breast height (d.b.h.) between 1 and 10 centimeters exceeds the retention target for that diameter class by 125 or more trees per hectare. About 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 meters tall and sufficiently dense in numbers to make cone collecting profitable.

Table 2—Outline of management practices, expected outcomes, and underlying assumptions at the Diamond Lake matsutake mushroom management area

Management practices	Expected outcomes	Underlying assumptions
Thinning the overstory	Thinning trees improves matsutake mushroom production.	Open stands have increased individual tree growth and nutrient cycling. Increased energy and water reach the soil. Fluctuations in available water and energy are more extreme.
Pruning low branches	Tree pruning improves matsutake 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 of branches prevents invasion by white pine blister rust. Butt logs of pruned trees produce more high-value, knot-free wood.
Spatially integrating mushroom and timber crops	Matsutake mushroom management and timber production from rust-resistant western white pines are compatible activities.	Matsutake 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 matsutake 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 matsutake mushrooms over time.
	Lodgepole pine is the best tree species to host matsutake mushrooms on burned sites and riparian sites.	Lodgepole pine regenerates best on disturbed, exposed surfaces. Lodgepole pine stands develop commercial matsutake mushroom colonies at high elevations.
	Shasta red fir is the best tree species to host matsutake 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 matsutake mushroom colonies.
Altering the organic litter layer	Increasing the amount of organic matter on the forest floor improves tree growth but depresses production of matsutake mushrooms.	Soil organic matter makes soil more fertile for tree growth. Thicker organic layers favor increased diversity of mycorrhizal fungi. Matsutake mushrooms do not compete strongly with most other fungi.
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 multiproduct agroforestry systems.
Retaining old-growth trees	Partial cutting retains old-growth trees and sustains productivity of matsutake mushroom colonies.	Old-growth trees are natural foci of matsutake mushroom colonies at high elevations.
Piling and burning slash	Fires reduce the survival of matsutake mushroom colonies.	Mycorrhizae and mycelia lie near the soil surface and are damaged by fire. Concentrating slash burns into small areas minimizes negative effects of fire on matsutake mushroom colonies.

Table 2 presents matsutake mushroom 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.

Table 3—Features of stands used in management experiments at the Diamond Lake matsutake mushroom management area

Stand feature	Stand 355	Stand 357	Stand 401
Elevation (meters)	1735	1705	1675
Aspect	NW to NE	NW to NE	W to NE
Slope (percent)	5	10-23	15
Position	Ridge	Mid to bottom of slope	Upper slope
Western white pine 100-yr site index (meters)	29	30	23
Basal area (m^2/ha)	24.6	53.4	60.1
Major overstory species[a]	MH	SF, MH	SF
Minor overstory species[a]	RF, WP	LP, WP	LP, WP
Understory species[a]	All 5 species	SF (MH)	SF, LP
Fungal infection[a]	WP, LP	WP, LP	WP, LP, RF
Mistletoe infestation[a]	SF, MH	SF, MH	—
Drought stress[a]	—	SF, MH	RF
Timber quality	Poor	Poor	Poor

[a] LP = lodgepole pine, MH = mountain hemlock, RF = Shasta red fir, SF = Pacific silver fir, and WP = western white pine.

Management Design

An experimental management approach increases the certainty that forest managers draw valid inferences about effects of management practices. Three stands are considered here to demonstrate a range of options available to land managers for improving joint resource production and revenue. Data from Umpqua National Forest stands 355, 357, and 401 are given in table 3. Within each stand, five replications were selected, each consisting of four plots. Each replication totals 9 hectares. Plots within replications were randomly assigned to one of three prescriptions or to the control treatment with no management. Each experimental plot covers 1 hectare and has a 25-meter-wide buffer treated the same way, for 2.25-hectare total forest area. The two 25-meter-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 matsutake 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.

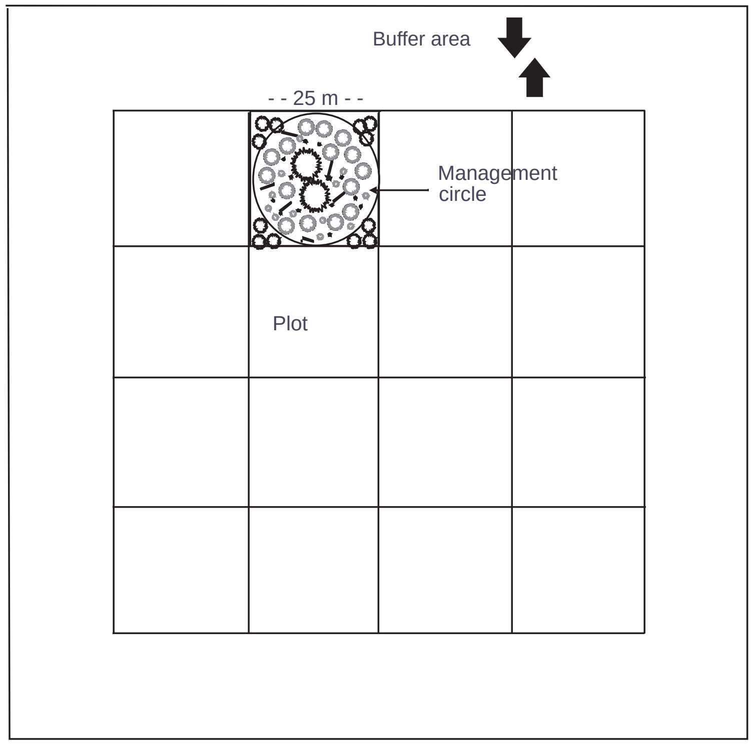

Figure 1—Plot configuration of one treatment.

Stands 355 and 401 retain old-growth trees of host species for matsutake mushrooms. Each experimental plot contains 16 management circles with 25-meter diameters. Figure 1 shows the schematic form of a plot surrounded by its buffer, and figure 2 depicts, from overhead, a matsutake mushroom management circle surrounded by interstitial cohorts of western white pine. Layout of management circles was designed to not disrupt the current distribution of matsutake mushroom colonies.

Where colonies already exist within a circular subplot, one or more anchor trees of the host tree species are designated by location and pattern of previous matsutake mushroom fruiting. Anchor trees are foci of colonies and will be retained indefinitely, potentially up to 800 years, as long as they do not infect gap and understory regeneration with pathogens that undermine tree growth. Individual management circles may not always have preexisting matsutake 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 matsutake 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.

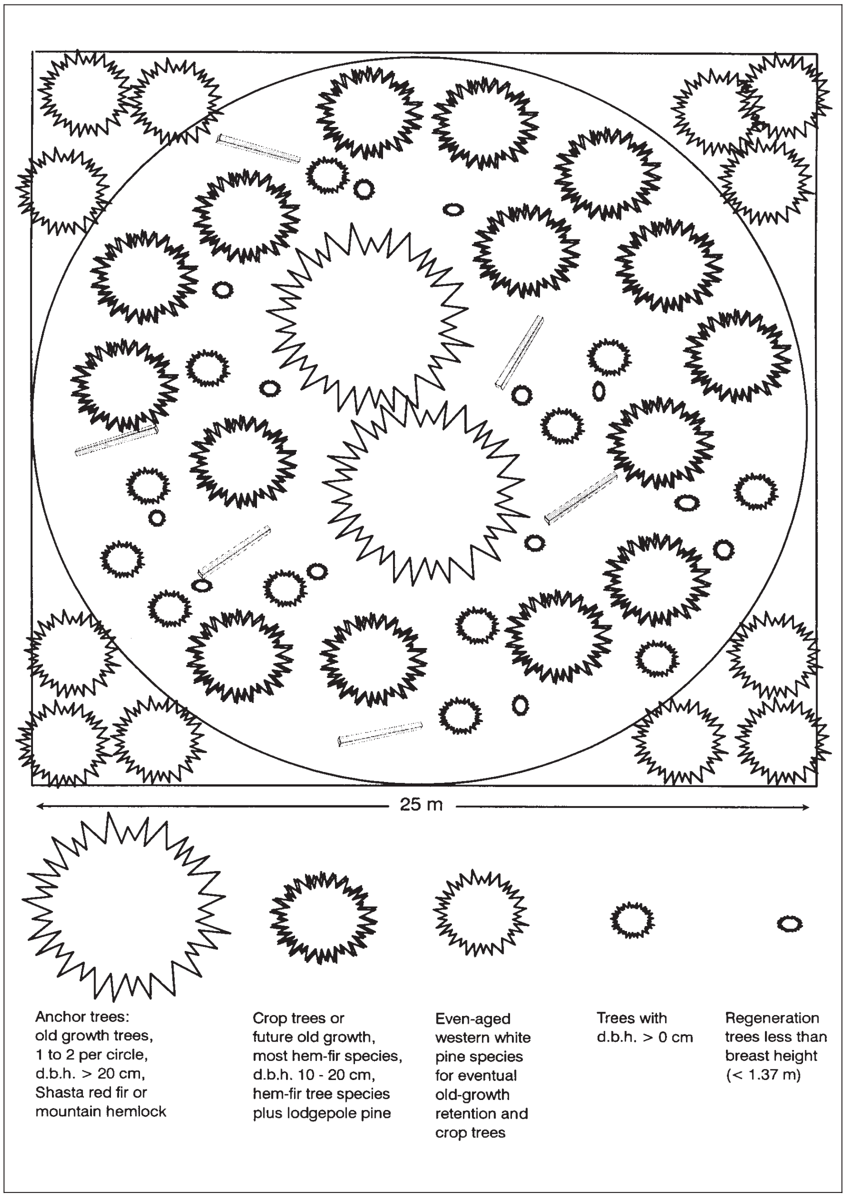

Figure 2—Generic scheme of a matustake mushroom management circle.

No vegetation management takes place in control plots. The only direct human manipulation is annual harvests of matsutake mushrooms. Comparison of mushroom yields between unmanaged plots and treatments 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 matsutake 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 premanagement 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 of the USDA Forest Service to restore western white pine into stands where it has disappeared after previous blister rust infections. Inclusion of western white pine is also a hedge if all efforts to manage matsutake mushroom colonies should fail. An important management consideration is whether western white pine trees, an apparent nonhost tree species for matsutake mushrooms, can be grown concurrently in stands also managed for matsutake mushrooms. One part of the management system is monitoring the response of western white pine to stand treatments intended to augment matsutake 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 nonhost 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 matsutake mushroom colonies and their host tree species into stands where host trees and matsutake mushrooms were previously absent.

Vegetation Patterns

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 matsutake mushroom production. Annual understory vegetation control of the kind typical for the understory in Japan or Korea 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 matsutake mushroom production indefinitely in uneven-aged forests.

Each of the stands presented here has a different set of treatments tailored to conditions in that stand. Treatments support stand management objectives. Experimental variations for stands are found in following sections. Details of stand management common to all three treatment prescriptions in a stand are then described in the appendices.

Experimental Management: Stand 355

The objective for experimental managment is to convert the stand to an uneven-aged structure.

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, multispecies stand that improves tree growth rates and increases in high-quality timber from western white pine in the long term
- make Shasta red fir and mountain hemlock the major host species for matsutake mushroom colonies to increase commercial production of matsutake mushrooms in the near term

Assumptions being tested are:

- relying on natural regeneration is the most cost-effective means for regenerating the desired species composition to provide host trees for matsutake mushroom colonies
- partial overstory removal creates and spreads matsutake mushroom colonies as well as increases commercial production
- pruning improves forest floor conditions for matsutake mushroom crops, increases timber value, and improves the resistance of matsutake species to fungus infection
- measures to improve production of matsutake mushrooms do not adversely affect western white pine tree growth

Table 4 outlines the objectives, experimental design, hypotheses, prescriptions for agroforestry systems, and one option for incorporating further experimentation. Figure 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—In year 0, **harvest** all trees taller than breast height except for:

- up to 30 Shasta red fir trees per hectare > 50 centimeters d.b.h., spaced with one to two 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 the 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 matsutake 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.

Table 4—Objectives, experimental design, hypotheses, and prescriptions for agroforestry systems, stand 355, Diamond Lake Ranger District

Objective	Strategies	Study design	Hypotheses	Prescriptions	Constraints
Draw greater revenue from high-elevation forests	Learn which management practices are most effective for increasing matsutake mushroom yields in stands dominated by Shasta red fir. Learn which practices and products jointly produce the highest net present value. Learn what spatial scale of gap disturbance works best to culture matsutake mushroom colonies. Learn how intensive management of mushroom colonies affects adjacent western white pines grown for high-quality timber.	Create 5 replications of 3 treatments plus a control plot. Treatments change 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 matsutake mushrooms and the vigor of colonies. Species in the overstory do not affect matsutake mushroom production or the vigor of colonies. Density control of overstory trees and tree regeneration increases production of matsutake mushrooms. Density control does not affect matsutake mushrooms.	1. Retain 30 old-growth Shasta red firs per hectare in 16 management circles per hectare 2. Retain 15 old-growth Shasta red firs per hectare and 15 old-growth mountain hemlocks per hectare in 16 management circles per hectare. 3. Retain 30 old-growth mountain hemlocks per hectare in 16 management circles per per hectare. 4. Control plot without treatment.	Maintain ecosystem processes. Retain original species diversity. Leave intact amenity values of aesthetics and recreation. Confine disturbances to the range and frequency of natural variation.
Additional option		Randomly design within each treatment replication a pruning/ no pruning treatment on regenerating trees in 8 of the 16 circles per hectare.			

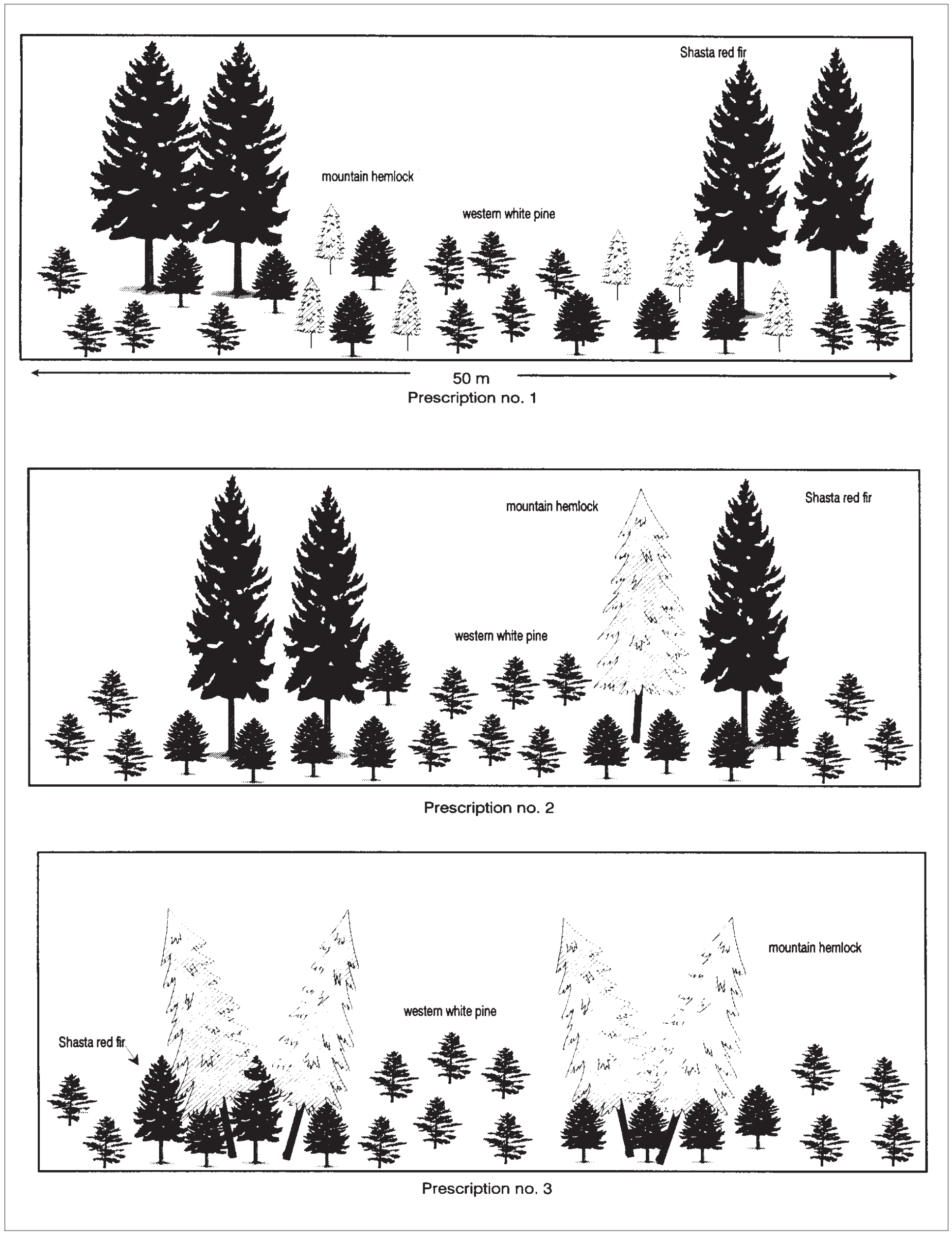

Figure 3—Projected stand structure for stand 355 in 25 years.

Target species for regeneration are Shasta red fir (600 trees per hectare), mountain hemlock (250 trees per hectare), and western white pine (250 trees per hectare).

In year 25, **thin** to meet targets for species retention:

mountain hemlock—

- retain the 250 most vigorous trees per hectare between 0 and 18 centimeters d.b.h.

Shasta red fir—

- retain the 250 most vigorous trees per hectare between 0 and 18 centimeters d.b.h.

Rationale: Stand thinning across all d.b.h. classes is necessary to maximize growth on individual trees and to select for trees of host species of matsutake mushrooms that have the greatest likelihood of advancing commercial production of matsutake mushrooms.

Prescription 2: Stand regeneration with a Shasta red fir/mountain hemlock overstory—In year 0, **harvest** all trees taller than breast height except:

- 15 Shasta red fir trees per hectare > 50 centimeters d.b.h.; and
- 15 mountain hemlock trees per hectare, with trees, regardless of species, spaced with one to two trees in each 25-meter-wide management circle as anchor trees.

Rationale: Overstory retention of old-growth mountain hemlocks and Shasta red firs may conserve long-lived matsutake mushroom colonies and allow for inoculation of young Shasta red fir regeneration. An understory lacking mountain hemlock regeneration and with a small number of Pacific silver fir trees interrupts the spread of dwarf mistletoe.

Target species for regeneration are Shasta red fir (850 trees per hectare) and western white pine (250 trees per hectare).

In year 25, **thin** to meet targets for species retention:

mountain hemlock—

- retain 15-30 trees per hectare > 50 centimeters d.b.h., one to three trees per 25-meter-wide management circle

Shasta red fir—

- retain 15-30 trees per hectare > 50 centimeters d.b.h., one to three trees per 25-meter-wide management circle
- retain the 500 most vigorous trees per hectare between 0 and 18 centimeters d.b.h.

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 matsutake mushrooms.

Prescription 3: Stand regeneration with a mountain hemlock overstory—In year 0, **harvest** all trees taller than breast height except:

- 30 mountain hemlock trees per hectare > 50 centimeters d.b.h. spaced with 2 to 4 trees in each 25-meter-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 matsutake 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 trees per hectare) and western white pine (250 trees per hectare).

In year 25, **thin** to meet targets for species retention:

mountain hemlock—

- retain 30 to 60 trees per hectare > 50 centimeters d.b.h., two to four trees per 25-meter wide management circle.

Shasta red fir—

- retain the 500 most vigorous trees per hectare between 0 and 18 centimeters d.b.h.

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 3: Stand regeneration with a mountain hemlock overstory—In year 0, harvest all trees taller than breast height except:

- 30 mountain hemlock trees per hectare > 50 centimeters d.b.h. spaced with 2 to 4 trees in each 25-meter-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 matsutake 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 trees per hectare) and western white pine (250 trees per hectare).

In year 25, **thin** to meet targets for species retention:

mountain hemlock—

- retain 30 to 60 trees per hectare > 50 centimeters d.b.h., two to four trees per 25-meter-wide management circle

Shasta red fir—

- retain the 500 most vigorous trees per hectare between 0 and 18 centimeters d.b.h.

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—In years 0 through 25, no vegetation management is planned. Harvests of matsutake mushrooms may occur every year. Management practices common to prescriptions 1 through 3 for stand 355 are given in appendix 1.

Experimental Management: Stand 357

The objective of stand management is to shift tree species composition and convert the current 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
- maximize net present stand value with a single product (timber) or a combination of products (timber and either mushrooms or Christmas trees)

Assumptions being tested are:

- emphasis on timber production using western white pine and a host tree species for matsutake mushroom colonies effectively alters stand composition for increased tree vigor and financial returns
- measures to improve production of matsutake mushrooms do not adversely affect western white pine tree growth
- tree species selection promotes matsutake mushroom production at sites without a history of commercial production of matsutake mushrooms

Table 5 summarizes the objective, experimental design, hypotheses, prescriptions, and one additional option for add-on research for adaptive learning. Figure 4 portrays the expected stand structure and composition cross sectionally 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 matsutake mushroom—This prescription changes stand structure and composition in two steps: first by thinning the Pacific silver fir population and introducing western white pine; then by 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.

In year 0, **harvest** all trees with heights greater than 1.37 meters and 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 trees per hectare less than 1.37 meters in height with good spacing, the longest crowns and best form.

Table 5—Objectives, experimental design, hypotheses, and prescriptions for agroforestry systems, stand 357, Diamond Lake Ranger District

Objective	Strategies	Study design	Hypotheses	Prescriptions	Constraints
Draw greater revenue from high-elevation forests dominated now by Pacific silver fir.	Learn whether changing tree species composition introduces matustake mushroom colonies into stands without previous matustake mushroom production. Learn which host tree species is best suited to regenerate on sites with mid to bottom slopes. Learn whether management of alternating generations of two host species promotes permanaent matsutake mushroom colonies under changing stand composition. Learn how intensive mushroom management affects western white pines for timber.	Create 5 replications of 3 treatments and a control plot. Treatments change the timing, the choice of species for recomposition, and the nontimber products cropped.	Management for timber and nontimber conifer products provides the best early stand income. Management for timber and matsutake mushroom crops provides the best early stand income. Lodgepole pine is the matsutake mushroom host species best suited to reforest moist sites. Mountain hemlock is the species best suited to reforest moist sites.	1. Retain 315 Pacific silver firs per hectare that are less than breast height for harvest as Christmas trees. Regenerate with mountain hemlock seed trees. 2. Retain 25 Pacific silver firs per hectare. Regenerate with mountain hemlock seed trees 3. Remove all but 25 Pacific silver firs and mountain hemlocks per hectare. Regenerate with lodgepole pine seed trees. 4. Control plot without treatment.	Maintain ecosystem processes. Obtain early income from the stand to cover costs for stand management costs. Improve biological diversity. Exclude fire as a tool to alter stand composition.
Additional option		Partition each treatment plot into 16 subplots and change stand density of regenerating trees to test effects on timber values and mushroom crops.			

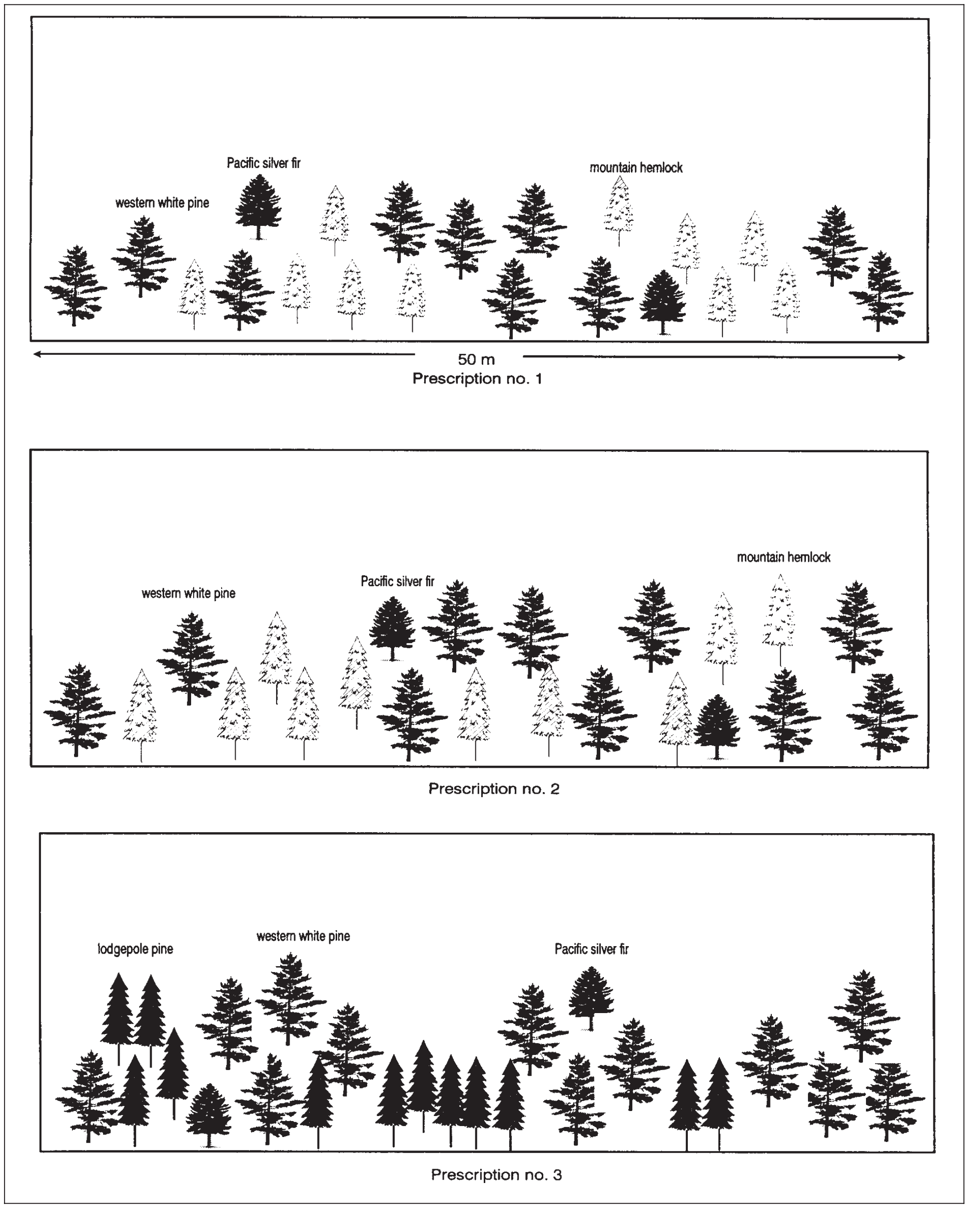

Figure 4—Projected stand structure for stand 357 in 25 years.

Rationale: Dense Pacific silver fir understory regeneration causes drought stress for these trees. By removing the overstory and reducing the density of regeneration, remaining trees develop open-grown foliage. Open-grown foliage on small Pacific silver fir trees makes them potentially merchantable as decorative boughs and Christmas trees[3] for early income from the stand.

Retain all mountain hemlocks less than 1.37 meters 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 (1,200 trees per hectare) and western white pine (500 trees per hectare).

In year 12, **harvest** Pacific silver fir trees for Christmas trees and boughs.

Rationale: Twelve years is hypothesized to be the time for residual Pacific silver fir trees to 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. 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.

In year 25, **thin** western white pine to 300 trees per hectare.

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 not slated for retention.

Rationale: This practice generates some income, improves health of western white pine, and reduces slash. Slash is piled and burned away from the site.

Thin mountain hemlock regeneration to 625 trees per hectare, and emphasize 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 matsutake mushroom colonies in the stand.

After year 25, this stand converts to producing matsutake 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 hemlock and western white pine, large gaps from thinnings around mountain hemlock anchor trees would promote disturbance without the 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.

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[3] Personal communication. 1996. Mark Savage, special forest products sales coordinator, State of Washington Department of Natural Resources, Olympia, WA.

Prescription 2: High-quality timber production based on western white pine, with prompt conversion of stand dominance to mountain hemlock and introduction of matsutake mushroom production—In year 0**, harvest** all trees with heights greater than 1.37 meters, except for mountain hemlock trees with d.b.h. > 10 centimeters that will be used 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 meters 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 matsutake mushroom production and better tree growth.

Target species for regeneration are western white pine (625 trees per hectare) and mountain hemlock (1,200 trees per hectare).

In year 5, **harvest** overstory mountain hemlock 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.

In year 25, **harvest** commercial-grade pine boughs from western white pine and possibly from mountain hemlock not marked for retention.

Rationale: This action reduces the amount of slash burned on a subplot in the buffer area, generates incomes from nontimber forest products, reduces stand leaf area index, and improves habitat conditions for matsutake mushrooms.

Thin mountain hemlock to 625 trees per hectare for retaining timber crop trees and future anchor trees in management circles.

Rationale: Crop trees or potential host trees for matsutake 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 matsutake mushroom colonies—In year 0, **harvest** all trees greater than 1.37 meters tall, except for lodgepole pine with d.b.h. > 10 centimeter that will be used 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 fir can promote lodgepole pine regeneration better than regeneration of other species.

Slash all but 25 trees per hectare each of Pacific silver fir and mountain hemlock regeneration less than 1.37 meters 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 matsutake mushroom productivity and better tree growth. Suppression of Pacific silver fir and mountain hemlock regeneration favors the predominance of lodgepole pine in stand regeneration.

Species targeted for regeneration are lodgepole pine (1,200 trees per hectare) and western white pine (625 trees per hectare).

In 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.

In 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 trees per hectare.

Rationale: These trees eventually will become crop trees, and residual trees can serve as focal trees for matsutake mushroom production.

Slash understory growth of all species, except mountain hemlock.

Rationale: Promoting mountain hemlock in gaps near clumps of lodgepole pine 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 while conserving matsutake mushroom colonies.

Prescription 4: Control plot—No vegetation management is planned. Harvests of matsutake mushrooms may occur every year. Management practices common to prescriptions 1 through 3 are given in appendix 2.

Experimental Management: Stand 401

The objective for experimental management is to convert the stand to an uneven-aged structure. 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 matsutake 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 by relying on natural regeneration

Assumptions being tested are:

- promoting young, naturally regenerating or planted Shasta red fir around other old-growth Shasta red fir is an effective method for expanding matsutake mushroom colonies
- relying only on natural regeneration with Shasta red fir is a cost-effective way to promote tree growth and augment matsutake mushroom production
- measures to improve matsutake mushroom production do not affect growth of western white pine
- retaining organic matter at mushroom harvest sites affects tree growth positively and depresses western white pine growth
- directing the species composition improves matsutake mushroom production

These prescriptions have the option of leaving chipped slash on one-half of 25- by 25-meter 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 matsutake mushrooms as compared to the practice of burning slash. Regeneration focuses on Shasta red fir management to produce matsutake mushrooms.

Table 6 summarizes the objectives, experimental design, hypotheses, prescriptions for agroforestry systems, and adaptive options for additional research. Figure 5 projects a schematic version of expected stand structure in 25 years.

Outline of Prescription Variables

Prescription 1: Matsutake mushroom management in uneven-aged stands with Shasta red fir canopy, young Shasta red fir filling gaps, and cohorts of western white pine—In year 0, **retain** 60 Shasta fir trees per hectare with d.b.h. between 18 and 50 centimeters 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.

Retain 60 Shasta red fir trees per hectare with d.b.h. > 50 centimeters with two to four trees per 25-meter-wide management circles as anchor trees.

Rationale: Old-growth Shasta red fir may be the foci of matsutake mushroom colonies. These trees maintain habitat for high-elevation old-growth wildlife species. Although old Shasta red fir 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.

Table 6—Objectives, experimental design, hypotheses, and prescriptions for agroforestry systems, stand 401, Diamond Lake Ranger District

Objective	Strategies	Study design	Hypotheses	Prescriptions	Constraints
Draw greater revenue from high-elevation forests dominated by Shasta red fir.	Learn whether matsutake mushroom production depends on density control of overstory trees.	Establish 5 replications of 3 treatments and a control plot. Treatments differ in the quantity of overstory canopy and the type of tree regeneration and timber products.	Shasta red fir trees spread new matsutake mushroom colonies faster to young trees.	1. Retain 60 Shasta red firs per hectare, 18 to 50 centimeters in diameter at breast height, as seed trees; and 60 trees per hectare, > 50 centimeters in diameter at breast height, as old-growth retention.	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 matsutake mushroom colonies.		Lodgepole pine trees spread new matsutake mushroom colonies faster to young trees.	2. Retain 60 lodgepole pines per hectare > 10 centimeters in diameter at breast height as seed trees, and 60 Shasta red firs per hectare, > 50 centimeters in diameter at breast height.	
	Learn whether volume and type of organic matter from trees changes soil chemistry and inputs of water and solar energy into the soil.		Amount of tree canopy affects production of matsutake mushrooms and the number of new colonies.	3. Retain 30 Shasta red firs per hectare, 18-50 centimeters in diameter at breast height as seed trees; and 30 Shasta red fir trees per hectare > 50 centimeters in diameter at breast height for old-growth retention.	
	Learn whether the volume of organic matter affects production of matsutake mushrooms.		Amount of tree canopy has a neutral effect on matsutake mushrooms.	4. Control plot without treatment.	
Additional option	.	Choose randomly 2 groups of 5 management circles from 1 treatment plot. Pile a fixed mass of organic litter collected from 1 group in each circle in the second group. The remaining 6 circles serve as controls.			

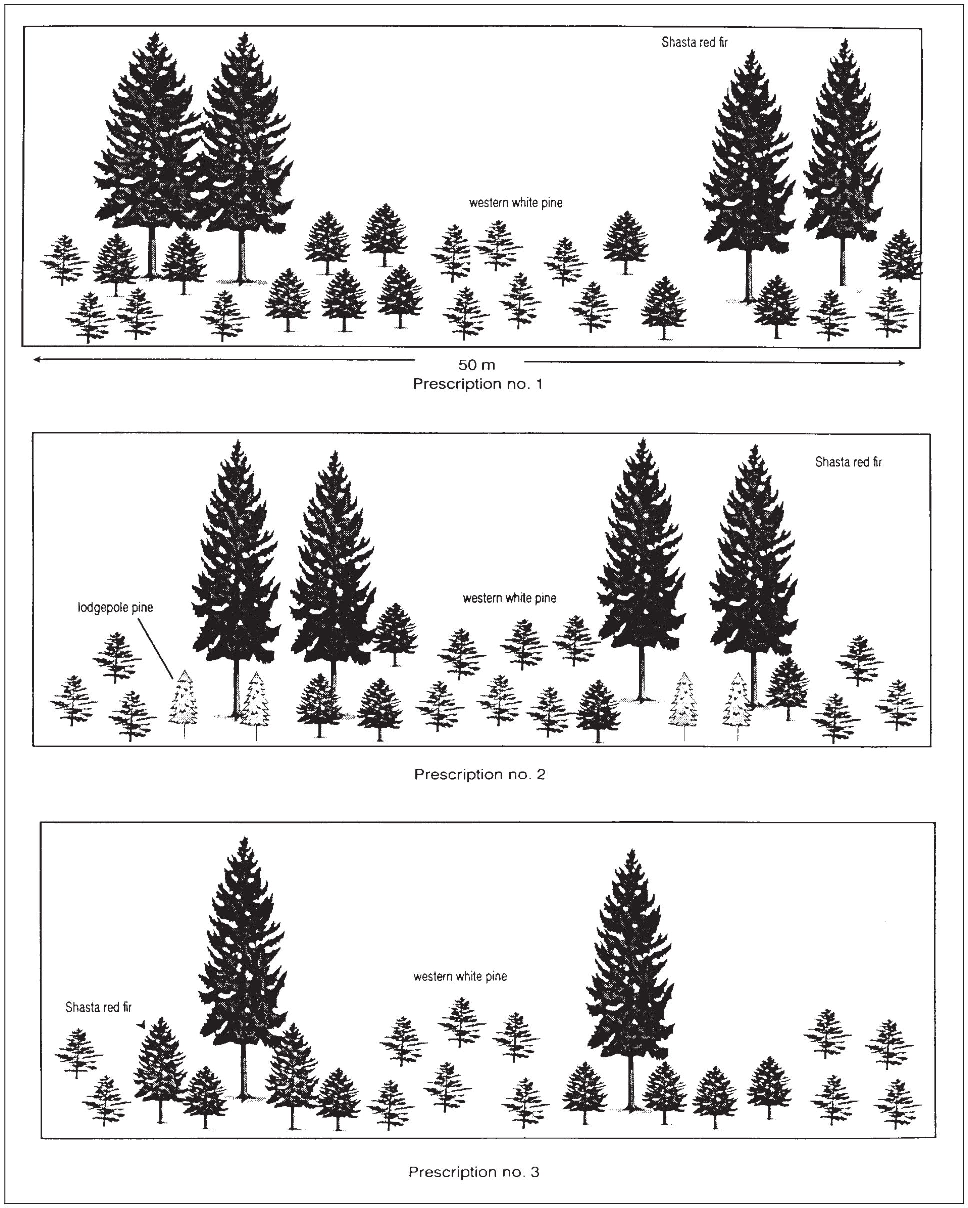

Figure 5—Projected stand structure for stand 401 in 25 years.

Chip unmerchantable slash and **leave** slash on site.

Rationale: Slashing unmerchantable lodgepole pine and excess Shasta red fir 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 trees per hectare) and western white pine (250 trees per hectare).

In year 5, **harvest** Shasta red fir seed trees between 18 and 50 centimeters d.b.h.

Rationale: Seed trees are removed so that treatments in each prescription are parallel and more growing space is provided for regenerating trees.

Prescription 2: Matsutake mushroom management in uneven-aged stands with Shasta red fir canopy, lodgepole pine filling gaps, and cohorts of western white pine—In year 0, **retain** 60 lodgepole pine trees per hectare with > 18 centimeters d.b.h. as seed trees. **Retain** 60 Shasta fir trees per hectare with > 50 centimeters d.b.h., with 2 to 4 trees per 25-meter-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 matsutake mushroom 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 unmerchantable Shasta red fir regeneration to favor only lodgepole pine regeneration.

Target species for regeneration are Shasta red fir (600 trees per hectare), lodgepole pine (600 trees per hectare), and western white pine (250 trees per hectare).

In 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 will increase the chance of passing gall rust infection to understory regeneration.

In year 15, **thin** for spacing to leave 40 lodgepole pine for each management circle, totaling 640 trees per hectare and favoring the most robust trees.

Prescription 3: Matsutake mushroom management in uneven-aged stands with less dense Shasta red fir canopy, young Shasta red fir filling gaps, and cohorts of western white pine—In year 0, **retain** 30 Shasta red fir trees per hectare, with d.b.h. between 18 and 50 centimeters, for seed trees evenly distributed across the stand.

Retain 30 Shasta red fir trees per hectare with > 50 centimeters d.b.h., with 1 to 2 trees per 25-meter-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 as in prescription 1 for suitable tree regeneration and commercial matsutake mushroom production.

Slash and **chip** remaining unmerchantable Shasta red fir regeneration to favor only lodgepole pine regeneration.

Leave chips on site.

Rationale: Slashing unmerchantable lodgepole pine and excess Shasta red fir 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 trees per hectare) and western white pine (250 trees per hectare).

In year 5, **harvest** all seed trees.

Rationale: Seed trees 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.

In year 15, **salvage** boughs and **slash** lodgepole pine and Shasta red fir to reduce stand density to a maximum 640 trees per hectare (40 trees per management circle) of the most robust regenerating trees, regardless of species.

Rationale: Spacing affords more rapid growth of remaining trees. 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—In years 0 through 25, **no management** is planned. Harvests of matsutake mushrooms may occur in every year.

Management practices common to prescriptions 1 through 3 are given in appendix 3.

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 7). 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.

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 production of matustake mushroom fruiting bodies 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 matsutake mushrooms in particular, remain poorly known.

Table 7—Response variables, techniques for sampling, and response variables units for management experiments, Diamond Lake matsutake mushroom management area

Response variable	Technique	Units
	Financial variables	
Matsutake mushroom production	Simulated commercial collection	kg/ha
Value of mushroom harvest	Recorded mushroom sale tickets	US$/ha
Timber harvest	Recorded timber scale tickets	mbf/ha
Timber harvest value	Recorded timber scale tickets	US$/ha
Commercial bough harvest	Recorded bough sale receipts	tonnes/ha
Commercial bough value	Recorded bough sale receipts	US$/ha
Matsutake cone crop mass	Recorded cone sale receipts	kg/ha
Value of matsutake cone crop	Recorded cone sale receipts	US$/ha
Christmas tree sales	Recorded sale receipts	US$/ha
	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
Soil moisture in autumn	Tensiometer	g/100 g
Soil nitrogen	Kjeldahl	g N/100 g
Soil temperature in autumn	Hourly thermometer readings in A1 layer	°C
Stand basal area increment	D.b.h. measurements of tree subsamples	$m^2 \bullet ha^{-1} \bullet yr^{-1}$
Matsutake mushroom mycorrhizae	Soil cores	number/ha
Fungal species diversity	Soil cores	number of species

Soil temperature, total solar radiation, effective precipitation, and soil moisture in the A1 (uppermost mineral soil) layer on sites with different treatments require daily, or even hourly, readings at critical times in matsutake 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 matsutake mushrooms.

Data on energy and water energy entering the soil column is critical to test, first, 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 increases in energy and rainfall at key times produce the desired stimuli in the top layer of the mineral soil to increase matsutake 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 matsutake 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 35 readings per treatment plot is advised.

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 microdisasters. Important information about matsutake mushroom ecology and the ability of matsutake mushrooms to recolonize burned sites can be found where slash residue from harvests in the matsutake 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 matsutake mushrooms and both Japenese red pine (*Pinus densiflora* Sieb. & Zucc.; Eto 1990) and Taiwan pine (*Pinus taiwanensis* Hay.; Hu 1994). Eventual success with similar artificial propagation using North American matsutake mushrooms and host tree species seems inevitable although initial efforts have been unsuccessful.[4] "Domestication" of matsutake mushrooms means, of course, that the supply of Asian matsutake 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. Matsutake mushroom crops from North America's native forests can meet rising demand from increasingly affluent eastern Asian countries and contribute even to world-class tourism targeted to mushroom hunters. The need to research and refine matsutake mushroom propagation and to plan stand-level culturing trials as management experiments is likely to meet needs of commercial and recreational pickers.

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 matsutake mushroom crops and high-quality timber is possible; foresters already have the silvicultural tools to implement treatments designed to further the ecological understanding of matsutake 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 asking questions to come up with creative and practical adaptive management experiments suited to the ecological conditions of forests under their management.

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[4] Personal communication. 1997. Michael Amaranthus, research forester, formerly with the Pacific Northwest Research Station.

Literature Cited

Alexander, E.B.; Mallory, J.I.; Colwell, W.L. 1993. Soil-elevation relationships on a volcanic plateau in the southern Cascade Range, northern California, USA. Catena. 20: 113-128.

Atzet, Thomas; Wheeler, David L.; Smith, Brad [and others]. 1992. Vegetation. In: Hobbs, Stephen D.; Tesch, Steven D.; Owston, Peyton W. [and others], eds. Reforestation practices in southwestern Oregon and northern California. Corvallis, OR: Oregon State University, Forest Research Laboratory: 93-113.

Atzet, Thomas; White, Diane E.; McCrimmon, Lisa A. [and others], tech. coords. 1996. Field guide to the forested plant associations of southwestern Oregon. Tech. Pap. R6-NR-ECOL-TP-17-96. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. [Irregular pagination].

Carlson, Garwin T. 1979. Winema National Forest soil resource inventory. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 156 p. [plus maps].

Chen, Jiquan; Franklin, Jerry F.; Spies, Thomas A. 1993. Contrasting microclimates among clearcut, edge, and interior of old-growth Douglas-fir forest. Agricultural and Forest Meteorology. 63: 219-237.

Cochran, P.H.; Boersma, L.; Youngberg, C.T. 1967. Thermal properties of a pumice soil. Soil Science Society of American Proceedings. 31: 454-459.

Cole, Dennis M.; Koch, Peter. 1995. Managing lodgepole pine to yield merchantable thinning products and attain sawtimber rotations. Res. Pap. INT-RP-482. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 14 p.

Cromack, K., Jr.; Entry, J.A.; Savage, T. 1991. The effect of disturbance by *Phellinus weirii* on decomposition and nutrient mineralization in a *Tsuga mertensiana* forest. Biology and Fertility of Soils. 11: 245-249.

Eto, Shinya. 1990. Cultivation of the matsutake seedlings infected with *Tricholoma matsutake* by use of *in-vitro* mycorrhizal synthesis. Bulletin of the Hiroshima Prefectural Forestry Experiment Station. 24: 1-6. In Japanese with English summary.

Everett, Yvonne. 1996. Building capacity for a sustainable non-timber forest products industry in the Trinity Bioregion: lessons drawn from international models. Network Pap. 20a. London, Great Britain: Overseas Development Institute, Rural Development Forestry Network: 24-37.

Fahey, Thomas D.; Willits, Susan A. 1995. Volume and quality of clear wood from pruned trees. In: Hanley, Donald P.; Oliver, Chadwick D.; Maguire, Douglas A. [and others], eds. Forest pruning and wood quality of western North American conifers. Inst. For. Resour. Contrib. 77. Seattle: University of Washington, College of Forest Resources: 115-126.

Franklin, Jerry F.; Carkin, Richard; Booth, Jack. 1974. Seeding habits of upper-slope tree species. I: A 12-year record of cone production. Res. Note PNW-213. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 12 p.

Franklin, Jerry F.; Smith, Clark E. 1974. Seeding habits of upper-slope tree species. II. Dispersal of a mountain hemlock seedcrop on a clearcut. Res. Note PNW-214. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest and Range Experiment Station. 51 p.

Grier, Charles C.; Lee, Katharine M.; Nadkarni, Nalini M. [and others]. 1989. Productivity of forests of the United States and its relation to soil and site factors and management practices: a review. Gen. Tech. Rep. PNW-GTR-222. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 51 p.

Hagle, Susan K.; McDonald, Gerald I.; Norby, Eugene A. 1989. White pine blister rust in northern Idaho and western Montana: alternatives for integrated management. Gen. Tech. Rep. INT-GTR-261. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 35 p.

Halverson, Nancy M.; Emmingham, William H. 1982. Reforestation in the Cascades Pacific silver fir zone. R6-ECOL-091-1982. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 37 p.

Hawksworth, Frank G.; Wiens, Delbert. 1996. Dwarf mistletoes: biology, pathology, and systematics. Agric. Handb. 709. Washington, DC: U.S. Department of Agriculture, Forest Service. 410 p.

Helms, John A.; Standiford, Richard B. 1985. Predicting release of advance reproduction of mixed conifer species in California following overstory removal. Forest Science. 31(1): 3-13.

Hobbs, Stephen; Tesch, Steven D.; Owston, Peyton, W. [and others], eds. 1992. Reforestation practices in southwestern Oregon and northern California. Corvallis, OR: Oregon State University, Forestry Research Laboratory. 465 p.

Hoff, Raymond J. 1992. Susceptibility of lodgepole pine to western gall rust within the middle Columbia River. Res. Note INT-RN-401. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 8 p.

Hosford, D.; Pilz, D.; Molina, R.; Amaranthus, M. 1997. Ecology and management of the commercially harvested American matsutake mushroom. Gen. Tech. Rep. PNW-GTR-412. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 68 p.

Hu, Hung-Tao. 1994. Study on the relationship between *Pinus taiwanensis* and *Tricholoma matsutake*. I: Semi-asceptic mycorrhiza synthesis of *Tricholoma matsutake* and *Pinus taiwanensis*. Quarterly Journal of Experimental Forestry of National Taiwan University. 8(3): 47-54.

Hungerford, Roger D.; Williams, Ralph E.; Marsden, Michael A. 1982. Thinning and pruning western white pine: a potential for reducing mortality due to blister rust. Res. Note INT-322. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 7 p.

Ishikawa, Takeshi; Tekeuchi, Sakae. 1970. Effects of forest irrigation on the occurrence of fruit-bodies of matsutake, *Tricholoma matsutake* Singer, and certain environmental conditions in the forest. Journal of the Japanese Forestry Society. 52: 362-386.

Ito, Takeshi; Ogawa, Maced. 1979. Cultivating method of the mycorrhizal fungus, *Tricholoma matsutake* (Ito et Imam) Sing. II: Increasing number of shiros (fungal colonies) of *T. matsutake* by thinning the understory vegetation. Journal of the Japanese Forestry Society. 61(5): 163-173.

Iwamura, M.; Nishida, T.; Ishikawa, T. 1966. Analysis of environmental factors in Japanese red pine forest producing the fruit body of matsutake (*Tricholoma [Armillaria] matsutake*). 1: The change of forest composition, light-intensity and the yield of fruit body in the treated matsutake forest. Scientific Reports of the Faculty of Agriculture 27, Okayama University: 17-26. In Japanese with English summary.

Kawata, Hiroshi; Kubo, Tetsushige; Arimitsu, Kazuto; Osumi, Yasuo, eds. 1981. Atlas of forest soil profiles in Japan. [Place of publication unknown]: Forestry and Forest Products Research Institute. 83 p. Vol. 2.

Kimble, J.M. 1993. Proceedings of the eighth international soil management workshop: utilization of soil survey information for sustainable land use; 1993 May; [location of workshop unknown]. Lincoln, NB: U.S. Department of Agriculture, Soil Conservation Service, National Soil Survey Center. 271 p.

Lee, Tai Soo. 1981. Ecological environments and yield production of matsutake in Korea. In: Report of the symposium on matsutake cultivation methods; 1987 October 7; [location of meeting unknown]. Seoul: Korea Forest Administration, Forestry Experimental Farm: 36-44. In Korean.

Lee, Tai Soo. 1983. Survey on the environmental conditions at the habitat of *Tricholoma matsutake* S. in Korea. Wood Science and Technology. 11(6): 37-44.

Lee, Tai Soo. 1989. Increasing yields and promoting quality of the matsutake mushroom by cap-covering or soil-covering. In: Mahadevan, A.; Raman, N.; Natarajan, K., eds. Mycorrhizae for green Asia: Proceedings of the first Asian conference on mycorrhizae; 29-31 January 1988; Madras, India. Madras: University of Madras, Centre for Advanced Studies in Botany: 224-230.

Lishman, Peter. 1995. Pruning lodgepole pine in southeastern British Columbia. In: Hanley, Donald F.; Oliver, Chadwick D.; Maguire, Douglas A. [and others], eds. Forest pruning and wood quality of western North American conifers. Inst. For. Resourc. Contrib. 77. Seattle, WA: University of Washington, College of Forestry: 337-341.

Mater Engineering, Ltd. 1992. Analysis and development of a conceptual business plan for establishing a special forest products processing plant. Corvallis, OR: Oregon State University Press. 234 p.

Meurisse, R.T. 1987. Forest productivity and the management of U.S. andisols. In: Kinloch, D.I.; Shoji, S.; Beinroth, F.H.; Eswaran, H., eds. Properties, classification, and utilization of andisols and paddy soils: Proceedings of the 9th international soil classification workshop; 1987 July 20-August 1; [location of meeting unknown]. [Place of publication unknown]: [publisher unknown]: 245-257.

Miller, Richard Alan. 1988. Native plants of commercial importance. Grants Pass, OR: Oak Publishing, Inc. 341 p.

Miron, Fernand. 1994. Woodland mushrooms: harvesting and marketing: testing, experimenting, and technological transfer in forestry project no. 4050. Sainte-Foy, PQ: Natural Resources Canada, Canadian Forest Service, Quebec Region. 56 p.

O'Hara, Kevin L.; Larvik, Darin A.; Valappil, Narayanan I. 1995a. Pruning cost for four northern Rocky Mountain species with three equipment combinations. Western Journal of Applied Forestry. 10(2): 59-65.

O'Hara, Kevin L.; Parent, Dennis R.; Hagle, Susan K. 1995b. Pruning eastern Cascade and northern Rocky Mountain species: biological opportunities. In: Hanley, Donald P.; Oliver, Chadwick D.; Maguire, Douglas A. [and others], eds. Forest pruning and wood quality of western North American conifers. Inst. For. Resourc. Contrib. 77. Seattle: University of Washington, College of Forest Resources: 216-237.

Page, Alan C.; Smith, David M. 1994. Returns from unrestricted growth of pruned eastern white pines. Bull. 97. New Haven, CT: Yale University, School of Forestry and Environmental Studies. 24 p.

Palazzi, Lisa M.; Powers, Robert F.; McNabb, David H. 1992. Geology and soils. In: Hobbs, Stephen D.; Tesch, Steven D.; Owston, Peyton W. [and others], eds. Reforestation practices in southwestern Oregon and northern California. Corvallis, OR: Forest Research Laboratory, Oregon State University: 48-72.

Pilz, D.; Fischer, C.; Molina, R. [and others]. 1996a. Matsutake productivity and ecology plots in southern Oregon. In: Pilz, D.; Molina, Randy, eds. Managing forest ecosystems to conserve fungus diversity and sustain wild mushroom harvests. Gen. Tech. Rep. PNW-GTR-371. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 75-77.

Pilz, D.; Molina, R.; Amaranthus, M. [and others]. 1996b. Matsutake inventories and harvesting impacts in the Oregon Dunes National Recreation Area. In: Pilz, D.; Molina, Randy, eds. Managing forest ecosystems to conserve fungus diversity and sustain wild mushroom harvests. Gen. Tech. Rep. PNW-GTR-371. Portland, OR: U. S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 78-80.

Radtke, Sherman; Edwards, Rudolph V., Jr. 1976. Soil resource inventory, Umpqua National Forest. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 218 p.

Redmond, Kelly T. 1992. Climate. In: Hobbs, Stephen D.; Tesch, Steven D.; Owston, Peyton W. [and others], eds. Reforestation practices in southwestern Oregon and northern California. Corvallis, OR: Forest Research Laboratory, Oregon State University: 74-90.

Russell, Kenelm. 1995. Sealing of pruning wounds and associated disease, and prevention of disease by pruning. In: Hanley, Donald F.; Oliver, Chadwick, D.; Maguire, Douglas A. [and others], eds. Forest pruning and wood quality of western North American conifers. Inst. For. Resour. Contrib. 77. Seattle: University of Washington, College of Forestry: 238-244.

Schlosser, William E.; Blatner, Keith A. 1996. Special forest products: an east-side perspective. Gen. Tech. Rep. PNW-GTR-380. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 27 p.

Shoji, Sadao; Nanzyo, Masami; Dahlgren, Randy. 1993. Volcanic ash soils: genesis, properties, and utilization. Amsterdam: Elsevier Publishers. 288 p.

Snellgrove, Thomas A.; Cahill, James M. 1980. Dead western white pine: characteristics, product recovery, and problems associated with utilization. Res. Pap. PNW-270. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 63 p.

Thomas, Margaret G.; Schumann, David R. 1993. Income opportunities in special forest products: self-help suggestions. Agric. Inf. Bull. 666. Washington, DC: U.S. Department of Agriculture. 206 p.

Totman, Conrad D. 1989. The green archipelago: forestry in pre-industrial Japan. Berkeley, CA: University of California Press. 297 p.

Tucker, Gabriel F.; Hinckley, Thomas M.; Leverenz, Jerry; Jiang, Shi-Mei. 1987. Adjustments of foliar morphology in the acclimation of understory Pacific silver fir following clearcutting. Forest Ecology and Management. 21: 249-268.

U.S. Department of Agriculture, Forest Service. 1996. Timber cut and sold convertible products report FS-1380. Portland, OR: Region 6 [Pacific Northwest Region]. Quarterly.

Villarreal, L. 1993. El “hongo blanco de ocote” en México: una perspectiva agroforestal para su manejo sostenible: Resumenes del I simposio internacional y II reunión nacional sobre agricultura sostenible; 1993 December 1-4, Puebla, México. [Place of publication unknown]: [publisher unknown]: 34. 2 vol.

Weigand, James F. 1997. Forest management for the North American pine mushroom (*Tricholoma magnivelare* (Peck) Redhead) in the southern Cascade Range. Corvallis, OR: Oregon State University. 500 p. Ph.D. thesis.

Appendix 1: Management Practices, Prescriptions 1-3, Stand 355

In year 0, **harvest** commercial-grade boughs from 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. Unmerchantable biomass is piled and burned away from the 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 trees per hectare blister rust-resistant western white pine stocks in cohorts of 15 between matsutake 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-meter intervals in the interstices of matsutake mushroom management circles. Western white pine are managed on a 100-year or longer rotation, with some old-growth retention trees eventually left at the site.

Retain nontarget species for stand species diversity as follows:

60 lodgepole pine per hectare and less than breast height, and

60 Pacific silver fir per hecatare and less than breast height.

In 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.

In year 15 (approximate), **harvest** boughs up to 1.2 meters high from western white pine and lodgepole pine trees > 2.4 meters in height 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, matsutake mushroom production is hypothesized to increase. Comparison with control sites serves to validate this hypothesis.

In 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 trees per hectare shorter than breast height, giving preference to open-grown trees.

Western white pine—Retain at least 125 trees per hectare, giving preference to the best spaced, largest, pruned, blister rust-resistant trees.

Lodgepole pine—Retain 60 trees per hectare 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 trees per hectare of old-growth retention trees. Plant western white pine in the same pattern as in year zero, except that the interstices are offset in a uniform direction by 5 meters.

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.) (Fahey and Willits 1995, Page and Smith 1994). Also, as part of restoration, remnant large western white pine are left on site to confer old-growth features.

Retain Shasta red fir or mountain hemlock trees to develop an enduring overstory of at least 30 old-growth (i.e., ≥ 50 centimeters d.b.h.) trees per hectare. At year 100, middle-aged western white pine and either Shasta red fir or mountain hemlock 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 will 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 matsutake mushroom colonies. This method is chosen as an alternative that simulates indefinitely midseral stand conditions to promote matsutake mushroom colonies while permanently retaining old-growth trees.

Appendix 2: Management Practices, Prescriptions 1-3, Stand 357

In year 0, **plant** 625 trees per hectare of blister rust-resistant western white pine seedlings on wide (4- by 4-meter) spacing for stand diversity.

Rationale: This enrichment planting raises the potential timber value of the stand considerably and helps to redirect the stand composition away from dominance by Pacific silver fir.

In year 0 and following years, **spread** matsutake mushroom sporocarps on and in the ground to introduce matsutake mushroom spores for inoculating small trees.

In 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 pine, where present, are harvested after year 75. A few residual trees function as seed trees around large gaps created by harvests of midstory mountain hemlock. Long-term uneven-aged management consists of alternating generations of lodgepole pine 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.

Appendix 3: Management Practices, Prescriptions 1-3, Stand 401

In year 0, **harvest** all commercial-grade boughs from trees not marked for retention.

Rationale: Harvesting of boughs generates some income to offset management costs, and 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 matsutake 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 meters and **retain** any naturally regenerated western white pines less than 1.37 meters 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 centimeters, with up to three anchor trees per management circles.

Rationale: Old Shasta red fir frequently host matsutake mushroom colonies. Retention of these old trees may allow for spread of matsutake mushroom to other younger trees growing in the vicinity of old anchor trees.

Plant 240 trees per hectare of 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 matsutake mushroom research site.

In year 25, **harvest** from below half of the basal area of all trees between 18 and 50 centimeters d.b.h.

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 no longer provide matsutake mushroom crops.

Thin western white pine to 80 trees per hectare, 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 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 and 17.7 meters.

After year 25, the stand emphasizes timber quality and annual matsutake mushroom harvests under management for joint production. Eventually three diameter classes make up the stand:

- an old-growth cohort of Shasta red fir retained indefinitely as anchor trees for matsutake mushroom colonies (>50 centimeters d.b.h.)
- a midsize cohort (18 centimeters < d.b.h. < 50 centimeters) of either Shasta red fir or lodgepole pine, or both, managed for timber production on long rotations and as eventual replacement trees for any dying anchor trees
- understory regeneration trees

The content of understory regeneration trees consists of lodgepole pine and Shasta red fir if the midsize cohort is made up of only Shasta red fir. Otherwise, the understory consists of Shasta red fir alone if the midsize cohort is made up of lodgepole pine or a mix of lodgepole pine and Shasta red fir. Both planted and naturally regenerated western white pine 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.

Appendix 4: Computer Source Code for Management Regimes

Each regime described in this paper is reproduced in QBasic computer source code for use in modeling with the program MUSHROOM (Weigand 1997). The nine regimes are reproduced in the ASCII file REGIMES.TXT on the diskette included with Weigand (1997). 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 no. 2 for stand 357 is found under subprogram CULTURE2357. QBasic software converts the ASCII-formatted subprograms directly to QBasic source code. Readers using other computer languages can likewise 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.

Weigand, James F. 1998. Management experiments for high-elevation agroforestry systems jointly producing matsutake mushrooms and high-quality timber in the Cascade Range of southern Oregon. Gen. Tech. Rep. PNW-GTR-424. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 42 p.

Experimental prescriptions compare agroforestry systems designed to increase financial returns from high-elevation stands in the southern Oregon Cascade Range. The prescriptions emphasize alternative approaches for joint production of North American matsutake mushrooms (also known as North American pine mushrooms; *Tricholoma magnivelare*) and high-quality timber. Other agroforestry byproducts 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 matsutake reproduction.

Key words: *Tricholoma magnivelare*, agroforestry systems, nontimber forest products, adaptive management, *Abies magnifica*, *Tsuga mertensiana*, *Pinus contorta*, *Pinus monticola*, *Abies amabilis*, tree pruning.

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