Chapter 4

Managing Structural and Compositional Diversity with Silviculture

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1. Introduction

Ecology, economy, and demography interact to affect forest management objectives. In the temperate rainforests of northwestern North America (Franklin and Halpern 1988), the outcome of this interaction for most of the 20th century was a management emphasis on wood production (Curtis et al. 1998, Haynes et al. 2003). Because of production efficiencies, even-aged, clearcut systems favoring harvest and regeneration of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) dominated regional silvicultural practices for decades (Tesch 1995, Curtis et al. 1998) (see Appendix 1 for all common and Latin names). By century end, however, economic and social conditions had changed (Haynes et al. 2003), and so had knowledge about forest ecology (Perry 1994, Franklin et al. 2002). Not surprisingly, different management objectives emerged. Indeed, although forest management in the 21st century still includes wood production, it is now just one of many objectives for regional forests (Kohm and Franklin 1997). Because management objectives and silvicultural practices are intertwined (Baker 1934, Daniel et al. 1979), this broadening of objectives is accompanied by a broadening of practices. Whereas earlier silvicultural practices simplified forest structure (arrangement and variety of elements) and composition (variety and amount of species present), the emphasis now is on managing diversity (O'Hara 2001). It is the concept of managing structural and compositional diversity that links silviculture to compatible forest management, which explicitly includes biological diversity (biodiversity) as an objective (Haynes et al 2002; Figure 5, Chapter 1).

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Silvicultural practices patterned on natural disturbance dynamics may conserve biodiversity in managed landscapes (Franklin et al. 2002, Lindenmayer and McCarthy 2002). This is a proposition being tested in the Pacific Northwest (PNW) (western Oregon and Washington, coastal British Columbia and southeastern Alaska; see Figure 1, Chapter 1), where silvicultural treatments are being developed to create conditions reminiscent of the biological legacies associated with natural disturbances (Cissel et al. 1998, Beese et al. 2001). Contemporary treatments, which are being applied both experimentally (Monserud 2002) and operationally (Beese et al. 2001), do not always coincide with treatments used in traditional even- and uneven-aged silvicultural systems (Mitchell and Beese 2002). Some of the treatments, for example, do not emphasize timber harvest or stand regeneration (Franklin et al. 1997), but instead create dead trees or other structures to benefit specific animal populations (Bull et al. 1995, Chambers et al. 1997).

Silvicultural treatments are often applied at the stand scale, but many can be used at other spatial scales as changing knowledge and objectives warrant (Curtis et al. 1998). This is important because the focus of forest management in the PNW is shifting from stands to watersheds and landscapes as knowledge about structural legacies and regional disturbance dynamics evolves (Swanson et al. 2003). Indeed, Spies and Johnson (2003) suggest that compatibility among forest resources may be scale dependent. Silvicultural treatments to enhance resource compatibility at the stand level thus may not do so at a different spatial scale, and vice versa.

This chapter discusses the importance of silvicultural science and practice for managing PNW forests to increase compatibility among resources. Compatibility occurs when forest management simultaneously produces wood and another resource without contributing to a decline in any other resource (Haynes et al. 2003). Section 2 reviews traditional silvicultural terms and systems and discusses their use in the PNW. Section 3 introduces contemporary silvicultural terms and treatments used when forest management objectives include biodiversity conservation and wood production. Section 4 considers evidence for potential compatibility among resources by reviewing the literature from regional studies of silvicultural treatments that include response variables related to biodiversity, aquatic resources, and wood—the key objectives of compatible forest management (Haynes et al. 2002; Figure 5, Chapter 1). The review identifies studies that include multiple resources and topics on which such studies are lacking (Appendix 2). The last section discusses information currently available, and that which is still needed, to manage structural and compositional diversity in PNW forests in support of enhanced compatibility among resources. Of particular importance is information about patterns and ranges of desired conditions that, in combination with site-specific information, will help silviculturists translate the concept of diversity into a system of treatments over space and time.

2. Traditional Silvicultural Terms and Their Use in the Pacific Northwest

Many silvicultural terms used in the PNW have remained essentially unchanged since their introduction to the English language (Curtis et al. 1998, O'Hara 2002) from Latin and German (USDA 1893, Troup 1928, James 1996). This chapter refers to such terms as traditional. A few are defined in this section (in **bold**), to give background for subsequent discussion on how traditional terms differ from, and contribute to, some contemporary terms now used in the PNW.

Silvics focuses on principles underlying the growth and development of single trees and of the forest as a biological unit (Hawley 1937, Smith 1986); it is synonymous with forest ecology (Toumey and Korstian 1937). By the 1920s, local research on the silvics of PNW trees began (Duncan and Miner 2000). As a result, extensive information is now available on the silvics of the conifers that dominate regional forests (Minore 1979, Burns and Honkala 1990a, Tesch 1995), particularly those with commercial value like Douglas-fir. In recent decades, knowledge on the silvics of other tree species (e.g., Sitka spruce, red alder, Oregon white oak) and associated vegetation has increased (e.g., Burns and Honkala 1990b, Tappeiner and Zasada 1993, Harrington and Kallas 2002, Wipfli et al. 2003).

Silviculture (*silva* = forest (Latin) + culture (English)) is the practice of altering forest ecosystems by using silvical knowledge and economic and social considerations (Daniel et al. 1979, Smith 1986). Most definitions of silviculture include three concepts: manipulating woody vegetation; influencing the establishment, growth, and composition of forests or woodlands; and achieving the goals of landowners and of society (e.g., Daniel et al. 1979, Smith 1986, Dawkins and Philip 1998, Helms 1998). Silvicultural science and practice provide information and methods for managing forested ecosystems over time and space in support of the objectives that people want.

A forest **stand** is a spatially continuous group of trees and associated vegetation growing on a site of similar soil and climate and having similar structure (Oliver and Larson 1990). **Structure** includes the horizontal and vertical distribution of forest components, including the heights and diameters of live and dead trees and the arrangement of foliage, crown layers, herbaceous plants, and down wood (Helms 1998, Spies 1998). A shift in community ecology in the 1980s (Perry and Amaranthus 1997) influences current views on forest stand development (Fujimori 2001). Patterns of stand development vary by species and site, yet are grouped into several stages, which describe key structures and processes typical of each stage. Stand development classifications used in the PNW include those by Oliver and Larsen (1990) and Franklin and Spies (1991); several others are displayed and compared in Appendix 1, Chapter 1. Although such classification methods can help link ecosystem processes and stand development (Fujimori 2001), they also have limitations. For example, structure-based classifications group continuous variables like diameter and foliage distribution, light conditions, and inter- and intra-specific competition into categories. Conceptual limitations resulting from categorizing forest ecosystems may now be impeding, rather than facilitating communication (Bunnell and Huggard 1999, Franklin et al. 2002) because of the various ways that different scientific disciplines regard structure (Appendix 1, Chapter 1). Further, such classification categories are usually qualitative rather than quantitative, and thus lack sufficient detail to be related empirically to biodiversity measures, such as species richness.

In this chapter, the first stage of stand development refers to the germination and establishment of trees and associated herbaceous vegetation. In the second stage, trees dominate a site, compete for growing space and nutrients, and crowns close to form a continuous canopy. In the third stage, tree crowns separate into different strata as density-dependent mortality occurs. Stage four shifts to density-independent mortality, and new trees and understory vegetation establish in available growing space. The fifth stage includes gap formation, continued mortality, and accretion of fallen dead trees. In the PNW, stages four and five are sometimes referred to collectively as "old-growth" forest. Because of the age-class distribution of forests available for studies of stand development after the 1980s, most existing data come from planted early—(first and second) stage or unmanaged late—(fourth and fifth) stage stands. Knowledge of the establishment and early development of existing late-stage forests in the PNW is derived from observational and reconstructive studies (Tappeiner et al. 1997a, Poage and Tappeiner 2002).

A **silvicultural system** is a planned series of treatments for a forest stand (Smith 1986), and implies a process for creating target conditions over time. The systems are classified either according to the regeneration methods used or by the number of tree age classes that result (Matthews 1989). **Even-aged** silvicultural systems secure a single cohort, or age class, of regeneration. **Age class** is variously defined, but generally implies that the difference in age between the oldest and youngest trees is no more than 20 years (Baker 1934), or not more than 20% of the rotation length (Smith 1986). **Rotation** is a term usually associated with even-aged systems and refers to the time between establishment and final harvest (Helms 1998). **Clearcutting** is an even-aged system that removes almost all trees, creating a fully exposed microclimate for a new age class to develop. In the PNW, clearcutting has predominated for a century (Tesch 1995, Curtis et al. 1998), and over this time rotation lengths have progressively decreased to 40 or 50 years (Curtis 1997, Wilhere 2003). After harvest, methods of site preparation and seedling planting ensure stand establishment is consistent with various state and provincial forest practices laws (Cleary et al. 1978, Arnott 1986, Cafferata 1986). Dependable methods for regenerating harvest units have removed the size restrictions on clearcuts that were previously imposed by the need for adjacent seed blocks for natural regeneration (Curtis and Carey 1996). Herbicides and fertilizers are sometimes applied, depending on landowner objectives, and various intermediate vegetation management treatments are typically done after stand establishment and before harvest, including weeding and release (Cafferata 1986). The latter are generally done in the first 5 years after planting, when sprouting shrubs or hardwoods (e.g., salal, vine maple) grow in conifer plantations (Tappeiner and Zasada 1993, Cafferata 1986). **Seed tree** systems also result in a single age class of regeneration. In this system, almost all trees are removed at harvest save a few kept for regenerating a new age class. Seed tree systems are not common in the PNW.

Two-aged silvicultural systems regenerate a stand with two age classes. **Shelterwood** systems, for example, cut most trees but leave some to shade the new age class establishing underneath. A shelterwood is distinguished from a seed tree system by the intentional use of shade, which gives desired species a growth advantage over competing vegetation during establishment. In contrast to trees retained in a shelterwood, which are generally harvested after a new age class is established, **reserve trees** are not typically removed. In the PNW, the main reason for experimenting with shelterwood systems was to observe regeneration responses in different forest types, including Douglas-fir (Williamson 1973), and western hemlock (Williamson and Ruth 1976). Considerable research on regeneration using shelterwood has been done (Tappeiner et al. 1997b), but use of this system has been limited to sites where ameliorating harsh conditions is important for stand establishment, such as in southwestern Oregon (Hobbs et al. 1992).

Other systems investigated have included strip thinning (McCreary and Perry 1983) and seed tree with reserves (Franklin 1963). The response variables of interest in these alternatives to clearcutting were often the quantity and distribution of natural reproduction (Seidel and Cooley 1974; Seidel 1979a,b, 1983).

Uneven-aged silvicultural systems regenerate a stand with three or more age classes. The objective is a forest with trees of different ages or sizes intermingled, typically accomplished with some form of selection system. In these systems, mature and immature trees are felled to create or maintain uneven-aged stands. **Single tree selection** fells individual trees and generally tends to increase the proportion of shade-tolerant species in mixed-species stands. **Group selection** cuts trees in units and therefore maintains a higher proportion of shade-intolerant species in mixed species stands than does individual tree selection. **Partial cutting** is a general term denoting something other than a clearcut; it can include selection systems. Experience with uneven-age silvicultural systems is limited in the PNW. In the decade before World War II, the regional forester instructed the supervisors of national forests in Oregon and

Washington to implement individual tree and small group selection with infrequent clearcut areas of “as much as 5 or 10 acres” (Buck 1934). This mandate to replace clearcutting in old-growth Douglas-fir forests with selection systems was controversial (Steen 1998, O’Hara 2002). By the 1940s, uneven-aged systems were abandoned in the PNW (Tappeiner et al. 1997b, Curtis et al. 1998), perhaps because of similarities with all-age systems used in Germany at the time (e.g., Dauerwald, Plenterwald) (Vogel 1990, Schabel and Palmer 1999). The current lack of information on the use of uneven-age silvicultural systems in the PNW is largely due to this earlier decision, which was based on limited data (Tappeiner et al. 1997b).

Plant ecology (Harper 1977, Koslowski et al. 1991) provides a basis for silvicultural theories on size-density relations (Hummel 2002). According to silvicultural theory, individual tree height and height growth are relatively unaffected by stand density, but tree diameter growth decreases with increasing density for both intraspecific and interspecific competition (e.g., see Knowe and Hibbs 1995 for review). Size-density relations imply that in plant populations—such as forest trees—growth reaches a point where some trees must die for others to get bigger (e.g., Weller 1987, Lonsdale 1990, Jack and Long 1996). Tree diameter is commonly used as a proxy for size in the PNW because it is easily measured and because early research in regional forests established relations between diameter and density (Reineke 1933).

Quantitative silviculture applies principles and models from plant ecology, size-density relations, and biometrics to make predictions about stand development (Jack and Long 1996). **Density management diagrams**, a quantitative tool used in the PNW (e.g., Drew and Flewelling 1979, Jack and Long 1996, Newton 1997), illustrate volumes and diameters associated with different numbers of trees per area and indicate how a stand is stocked relative to a maximum density (e.g., McCarter and Long 1986, Long et al. 1988). The diagrams are species-specific, and derived primarily from research in even-aged, single-species stands. They are used to guide spacing and stocking decisions and to design thinning schedules for various objectives, such as timber production or habitat structure (Smith and Long 1987, McTague and Patton 1989, Sturdevant et al. 1996, Ferguson and Archibald 2001).

Thinning is a treatment to reduce tree density (Helms 1998). **Precommercial thinning** implies that trees cut are not merchantable, whereas in **commercial thinning** the trees are valuable enough to recover harvest costs (Helms 1998). When trees are cut from the lower crown classes to favor those in the upper classes, the term used in the PNW is **thinning from below**. In contrast, **thinning from above** involves cutting dominant and co-dominant trees to favor the best trees of these classes (Helms 1998). By the 1950s, precommercial thinning was adopted throughout the PNW as a way to regulate spacing in plantations and to select future crop trees. Commercial thinning was not widely adopted, however, (Curtis et al. 1998) because selling old-growth timber and establishing short-rotation (40 to 60 year) plantations was more profitable than selling logs from commercial thinning operations (Curtis and Carey 1996). Now, however, this situation has changed and there is interest in combining commercial thinning with rotations of 100 years or more (Curtis 1997).

3. Contemporary Silvicultural Terms and Their Use in the Pacific Northwest

Ecological knowledge about the dynamics of PNW forests gained in recent decades is influencing silvicultural science and practice. As a result, scientific and forest management literature from the PNW contains a mix of traditional and contemporary silvicultural terms. The latter are emerging as treatments develop in response to forest management objectives that include biodiversity conservation and wood production. This section introduces some contemporary silvicultural terms (in *italics*) and associated treatments now being used in the PNW. The treatments share the objective of creating structural and compositional diversity but have different names, owing to the place or date of their origin. Further, use of treatments with the same name varies between agencies such as the U.S. Departments of Agriculture and the Interior (USDA/USDI 1994). The lack of a common lexicon and usage is confusing; it is also evidence of the transition occurring in PNW forest management. Ongoing discussion about traditional versus contemporary silvicultural terms (e.g., Franklin et al. 1997, Buermeyer and Harrington 2002) stems in part from debate about contemporary treatments and whether these treatments describe a target condition or a system by which a target condition is perpetuated (Mitchell and Beese 2002).

3.1. Biodiversity Conservation

Conservation of biodiversity as a goal of forest management is widely (e.g., Fenger 1996, Lähde et al. 1999) but not completely (Zavala and Oria 1995) accepted, in part because relations among biodiversity, ecosystem resilience and stability, and disturbance remain unclear (Perry and Amaranthus 1997, Symstad et al. 2003). For this reason, Simberloff (1999) argues that conservation of biodiversity in managed forests must rely on a commitment to biodiversity as an intrinsic value.

Several contemporary silvicultural treatments used in the PNW are designed to support a management objective of conserving biodiversity. *Green-tree retention*, for example, is a stand management treatment that leaves live trees, snags, and down wood within harvest units to provide structure over the next management cycle (USDA/USDI 1994). Green trees are not removed after a new age class has established but instead are left on site (Beese and

Bryant 1999) to provide structures thought to be vital for birds and other animals (Franklin et al. 1997). Green-tree retention may be considered synonymous with reserve trees (Helms 1998), but these two terms are not interchangeable in PNW literature (Franklin et al. 1997, Buermeyer and Harrington 2002). Green trees are sometimes deliberately killed to create snags (Chambers et al. 1997) and, depending on how they are arrayed spatially, the terms dispersed retention or aggregated retention are used (Franklin et al. 1997). *Dispersed retention* refers to retaining live and dead trees distributed evenly over a harvest unit, whereas in *aggregated retention* the trees are clumped (USDA/USDI 1994, Franklin et al. 1997). The two methods carry different implications for the costs, safety, and effects of harvest operations (Moore et al. 2002, Wilhere 2003), and may provide different habitat values for various species (McComb and Lindenmayer 1999).

On forests in the United States within the range of the northern spotted owl (*Strix occidentalis caurina*), a federal plan mandates different land allocations or management zones (USDA/USDI 1994). The zone where scheduled timber harvest can occur, the matrix land, offers an example of green-tree retention (USDA/USDI 1994). On matrix land administered by the U.S. Department of Agriculture, the general prescription requires that 15% of the area of each cutting unit be left unharvested. At least 70% of this leave area must be covered by patches bigger than 1 hectare (ha) (aggregated retention), and the rest must be spread across the cutting unit as single trees or smaller patches (dispersed retention). In addition to trees, down wood must also be retained: 240 linear feet of logs per acre (181 meters (m)/ha) greater than 20 feet (6.1 m) long and 20 inches (50.1 centimeters (cm)) in diameter. In contrast, on land administered by the U.S. Department of the Interior in the southern portion of the PNW, the general prescription calls for retaining 16 to 25 large green trees per acre (40 to 60 trees per ha) in harvest units, without mention of retention pattern (USDA/USDI 1994).

Variable retention is a term used when trees are left distributed throughout harvest areas to provide structural diversity. Variable retention is a form of partial cutting (Beese et al. 2001) and is based on the concept that natural disturbances leave residual structures thought to be important for ecosystem function and biological diversity (Franklin et al. 1997). The structures emphasized are live and dead trees of varying sizes, multiple canopy layers and coarse woody debris (Franklin et al. 1997, Beese and Bryant 1999). Retention of these structural features during logging operations is hypothesized to sustain biological diversity by providing a place for species that used the features prior to harvest; indeed a key assumption is that these retained features will be the basis for reestablishing species once the harvested area has grown into a suitable condition (Franklin et al. 1997).

The term variable retention was created because traditional silvicultural terms were not legally adequate to describe management objectives in coastal

British Columbia (Mitchell and Beese 2002). The definition, now codified in British Columbia legislation, includes two features that characterize variable retention: (1) long-term structural diversity and (2) sufficient structure remaining to maintain forest influence on the harvested area (Mitchell and Beese 2002). The former is provided by trees retained in either groups (aggregated retention) or as individuals (dispersed retention) for at least one rotation, whereas the latter results from the requirement that no more than one tree length exist between retained trees (Mitchell and Beese 2002). Variable retention is being combined with traditional silvicultural systems such as shelterwood and group selection (Beese et al. 2001). Variable retention is, therefore, not synonymous with uneven-aged systems. Rather, variable retention describes a target condition that avoids structural simplification regardless of the silvicultural system used.

In 1998, the forest products company McMillan Bloedel adopted variable retention to guide management on private and tenured Crown forests in British Columbia. The decision was made in response to social concerns (Beese et al. 2001), and was continued by Weyerhaeuser when it acquired McMillan Bloedel a year later. Although monitored at the stand scale, variable retention on public land managed by Weyerhaeuser is being applied in landscape zones that range from 5000 to 50 000 ha. Three zones exist, each with a different emphasis: old growth, habitat, and timber; Beese et al. (2001) describe the retention and harvest intensity gradient that occurs among them. Ten percent of land managed by Weyerhaeuser is in the old-growth zone. Here, 33% of the landscape is available for group selection and irregular shelterwood harvest, but 20% retention is required at the unit level. In the habitat zone, which covers 25% of land managed by Weyerhaeuser, 70% is available for harvest using a range of silvicultural systems; within units, 15% retention is required. Finally, the most intensive zone is timber, which covers 65% of land managed by Weyerhaeuser. In the timber zone, 80% of the total area is available for harvest through group retention (10%), dispersed retention (5%), and shelterwood systems.

Another contemporary term encountered in PNW literature is *variable density* (USDA FS 2003), which describes thinning treatments that avoid regular spacing among residual trees. It has arisen from concern over the extensive area of structurally uniform, second stage Douglas-fir plantations in the region that are a result of post-World War II clearcutting practices (Hunter 2001). Variable density thinning is a treatment being used in early-stage forests to accelerate the development of structural and compositional diversity observed in late-stage forests (Muir et al. 2002), and to investigate associated effects on small mammal populations (Carey 2001).

These contemporary treatments share the premise that structural and compositional diversity in managed forest ecosystems is better than uniformity. Diversity is the target condition. Translating this target into a process by which diversity is created and maintained over time and space requires site-specific information. It also requires using, observing, and adjusting treatments over time; a practice sometimes referred to as adaptive management (e.g., Nyberg and Taylor 1995) or monitoring (Mitchell and Beese 2002). Actual outcomes will likely differ from expectations as, for example, when converting even-aged uniform stands to uneven-aged species mixtures (Nyland 2001, O'Hara 2001). As experience is gained, and as data are available that relate specific silvicultural treatments to biodiversity over space and time, modifications to the treatments currently being applied will occur and silvicultural systems for managing structural and compositional diversity will be developed. These could include extending rotations over several hundred years in combination with commercial thinning (Curtis 1995, Curtis 1997, Busing and Garman 2002), relying on natural regeneration from group selection (Worthington 1953) or retention (Buermeyer and Harrington 2002), and favoring species mixtures that include hardwoods.

3.2. Wood Production

Management primarily for wood production is concentrated on private industrial land in the PNW (Curtis et al. 1998, Haynes et al. 2003), and associated silvicultural practices often include intensive site preparation and vegetation management. State and provincial forest management is less intensive but still includes wood production; federal forest management has a decreasing emphasis on wood production. Wilhere (2003) gives an example of practices on industrial forestland in the PNW: (1) 2-year-old Douglas-fir seedlings from a nursery are planted at 1075 trees per hectare (tph); (2) at age 15, stand is precommercially thinned from below to a residual density of approximately 740 tph; (3) at age 30, stand is commercially thinned from below to a residual density of approximately 340 tph; and (4) at age 50, stand is clearcut.

Quantitative silvicultural tools developed from single-species, even-aged stands make it possible to estimate yield associated with various species, site conditions, and stand ages by using density management diagrams and growth and yield models (Monserud 2003). If, however, the objective is wood production from mixed-species or uneven-aged stands, then comparable tools are not yet available. Their development requires better knowledge about the dynamics of mixed species stands and the response of such stands to specific treatments. For example, data on the effects of residual trees on the growth and yield of regeneration are limited (Zenner et al. 1998, Mitchell 2001), as is information about maximum density in mixed species stands (Puettmann et al. 1992, Shaw 2000).

Forest management in the PNW is creating divergence in forest age classes (Harris 1984, Figure 3, Chapter 1). Older age classes (fourth and fifth stages) tend to be on public land whereas the younger age classes (first and second stages) tend to be on private land. Recent studies indicate this trend will continue (Spies and Johnson 2003). This predicted age class distribution, and potential age class gap (third stage), is prompting discussion about management practices that might support a full array of forest age classes, structures, and processes in the region.

4. Evidence for Compatibility Among Different Objectives

The previous section described silvicultural treatments for achieving either biodiversity conservation or wood production in the PNW. Compatibility implies not having to choose between these two objectives but managing for both simultaneously without a decline in other forest resources (Stevens and Montgomery 2002, Haynes et al. 2003). This section reviews the literature from regional studies of silvicultural treatments that include multiple response variables related to biodiversity, aquatic resources, and wood because these are the key objectives of compatible forest management (Haynes et al. 2002; Figure 5, Chapter 1). The objective is to identify results from PNW studies that directly address potential compatibility among forest resources.

4.1. Biodiversity

Biodiversity includes genetic, species, and ecosystem diversity (Wilson 1988). Compositional diversity refers to the number of elements in a system; structural diversity refers to the physical organization; and functional diversity refers to the different processes (Zavala and Oria 1995). In this chapter, species richness is adopted as a proxy for compositional diversity; therefore, studies that focus on species abundance or dominance are not emphasized. Silvicultural treatments directly affect stand composition and structure, so most studies investigating effects of silvicultural treatments on biodiversity measure compositional or structural alpha diversity; a few investigate treatment effects on processes such as decomposition (Appendix 2).

Birds, small mammals (Carey 2003), and understory plants (Kerns et al. 2003) are the focus of most studies investigating compositional diversity associated with silvicultural treatments (Appendix 2). Studies of structural diversity, including wildlife habitat elements, generally investigate the vertical and horizontal distribution of living or dead trees and shrubs. Most designed experiments and observational studies investigating compositional and structural diversity associated with silvicultural treatments in the PNW are less than 100 ha (Appendix 2). The studies cover a range of forest types (key tree species are noted parenthetically).

Most studies that apply silvicultural treatments along a gradient of tree removal intensity and compare species richness values to an untreated control focus on birds (Appendix 2). None of these studies report the wood volume, quality, or potential product values associated with the different treatments. Treatment effects on bird species richness are mixed; some studies report no difference whereas others report increases or decreases. For example, in a replicated study on Vancouver Island, British Columbia, shelterwood, patch clearcut, and clearcut with reserves (green-tree) treatments were applied to coastal montane forest (*Abies amabilis/Tsuga heterophylla/Thuja plicata/Chamaecyparis nootkatensis*). After 3 years, the species richness of breeding birds was reduced in all treatments (Beese and Bryant 1999). The uncut control had significantly more breeding bird species than any treated unit; the shelterwood and green-tree retention were similar in terms of richness. Likewise, the species richness of winter resident birds was higher in the uncut control than in treated units, which were ranked in descending order (patch cut, shelterwood, green-tree). In another replicated study, this one from Douglas-fir dominated forests of the Oregon Coast Range (*Pseudotsuga menziesii/Abies grandis/Acer macrophyllum/Quercus garryana*), wintering (Chambers and McComb 1997) and breeding (Chambers et al. 1999) bird responses to three silvicultural treatments (small-patch group selection, green-tree, and modified clearcut) were measured. No treatment effects on species richness of breeding birds were detected after 2 years, although more species were observed in the green-tree than in the other treatments, and the small-patch group selection was most similar in composition to control stands (Chambers et al. 1999). Like Beese and Bryant (1999), Chambers et al. (1997) report treatment effects on the species richness of winter resident birds, but the latter report more species in the small-patch group selection than in control and modified clearcut stands. In a retrospective study comparing commercially thinned and unthinned Douglas-fir stands in the Oregon Coast Range, Hagar et al. (1996) found that breeding and winter bird species richness did not appear affected by thinning that occurred 4 to 15 years prior to their observations. However, the density of hardwoods 31 to 43 cm diameter at breast height (dbh) was an important predictor of bird species richness, and this density did not differ between thinned and unthinned stands (Hagar et al. 1996).

Despite a lack of long-term experiments on patterns of regional bird species richness, Olson et al. (2001) provide some general observations:

- Species richness tends to be similar in early (first stage) and late (fourth and fifth) stage forests and lowest in mid stages (second and third)
- Mean species richness of diurnal breeding birds is higher in the Coast Range than in the Cascade Range (owing to a generally negative correlation with latitude and positive correlation with longitude in western Oregon and Washington)
- Species richness increases with vegetation height

Experimentally investigating these observations in association with different types and intensities of treatment will contribute information that can be used to evaluate potential compatibility among forest resources. Overall, results to date indicate that the response of breeding and wintering birds to forest structures created via silvicultural treatments differs by species. There are too few data from long-term, replicated studies in the PNW, however, to identify if specific response patterns exist and, if so, what they might be. This suggests that a mix of stand developmental phases and structures are important for bird species diversity, but does not identify the specific mixture or spatial pattern. Information on demographic performance of species (e.g., reproduction and survival) is needed (DeStefano 2002) to assess potential treatment effects that are not evident in species richness measures, such as nest predation (Tittler and Hannon 2000) and parasitism (Chambers et al. 1999). For example, an increase in brown-headed cowbird (*Molothrus ater*) abundance was noted by Chambers et al. (1999) in green-tree retention treatments of Douglas-fir; a similar observation was made by Bull et al. (1995) in a case study of a modified selection treatment in mixed-conifer forests of northeastern Oregon (*Abies grandis/Pseudotsuga menziesii/Pinus contorta/Larix occidentalis/Pinus ponderosa*). Brown-headed cowbirds are an obligate brood parasite that can contribute to declines in bird populations, but parasitic effects associated with different treatments are not clear (Bull et al. 1995, Chambers et al. 1999).

Information on species richness associated with different types and intensities of silvicultural treatments is sparse for birds but it is even sparser for other vertebrate and invertebrate species. Studies of mammals generally report species abundance (e.g., Wolff and Zasada 1975, Cole et al. 1998, Carey 2001, Gitzen and West 2002) rather than richness, and are often observational (Appendix 2). None of the published studies on mammals report the wood volume, quality, or potential product values associated with silvicultural treatments. Arthropod diversity is described by Schowalter (1995) for partially-harvested, late-stage and early-stage Douglas-fir forests in the central Oregon Cascade Range.

Research on plant species richness associated with silvicultural treatments focuses on herbaceous understory species (Appendix 2) (Kerns et al. 2003). Treatment effects on understory species richness are mixed, but greater numbers are often associated with shelterwood systems. Species identification may be more important than mere enumeration if management objectives include minimizing the establishment or spread of non-native (exotic) species. For example, Bailey et al. (1998) observed that understory plant species richness was greater in thinned than in unthinned Douglas-fir forests in western Oregon; but they noted that exotic species contributed to observations of increased richness. In a replicated study on Vancouver Island, British Columbia, 3 years after treatments were applied to coastal montane forest (*Abies amabilis/Tsuga* *heterophylla/Thuja plicata/Chamaecyparis nootkatensis*), Beese and Bryant (1999) found that understory plant species richness in the shelterwood was significantly higher after treatment than before, but no significant difference existed among the clearcut, patch clearcut, or green-tree treatments. South of the PNW region, in the mixed-species conifer forests of the northern California Sierra Mountains, Battles et al. (2001) compared understory vascular plant diversity in stands treated with shelterwood, single tree selection, group selection, and no active management (reserve units). They found that even-age methods were associated with the highest species richness, whereas reserve units and single tree selection methods were the least rich. Uneven-age methods had greater proportion of late-seral species and fewer exotic species than shelterwoods.

4.2. Structural Diversity

Information about the effects of silvicultural treatments on forest structures is needed to evaluate the proposition that treatments designed to create structural diversity, such as variable retention, conserve biodiversity. Structural elements hypothesized to be important for biodiversity conservation include live and dead trees of different sizes, multiple canopy layers, and coarse woody debris; hence they are emphasized in current PNW literature. Most published studies focus on the effects different treatments and intensities have on these structural elements; none relate their presence or abundance to species richness of multiple taxa (Appendix 2), although Chambers et al. (1997) investigated the use of artificially created Douglas-fir snags by cavity-nesting birds. Evidence is currently insufficient, therefore, to evaluate whether silvicultural treatments to create diverse forest structures conserve biodiversity better than those that result in structural simplification. Data from several regional long-term, large-scale experiments installed in the 1990s (Monserud 2002) are becoming available, however, and continued investment in these studies will help evaluate relations between forest structure and biodiversity.

Reports of structural elements associated with silvicultural treatments focus on standing or down dead trees and on woody debris (Halpern and McKenzie 2001), conifer regeneration in montane British Columbia (Mitchell 2001) and the Cascade Range in southwestern Washington (Buermeyer and Harrington 2002), live tree growth and density in Alaska (Deal and Tappeiner 2002), and understory plant strata (Bailey et al. 1998) (Appendix 2). Halpern and McKenzie (2001) considered effects on the structural attributes of ground cover, slash depth, and woody debris associated with the retention level (15% and 40%) and pattern (aggregated versus dispersed) on four treatment units at six locations in the Cascade Range of Washington. At the lowest retention level there was greater depth and cover of slash, and less woody debris; in general, aggregated retention had higher covers of slash and dispersed retention had greater variation in slash cover and depth (Halpern and McKenzie 2001). Down wood is created indirectly after treatment via windthrow, which Beese and Bryant (1999) discuss in relation to shelterwood, patch clearcut, and clearcut with reserves (green-tree) in three replicates of coastal montane forest in British Columbia. Three years after treatment, 25% of the reserve trees in the green-tree retention unit were down, compared to 5% in the shelterwood; more trees in the intermediate crown class (22%) blew down in the green-tree retention unit than did trees in dominant (7%) or codominant (10%) crown classes (Beese and Bryant 1999). Although these windthrown trees add to woody debris levels, these measurements were not reported.

In a retrospective study in southeastern Alaska, Deal and Tappeiner (2002) investigated species composition, understory plant diversity, and tree size diversity in Sitka spruce-dominated forests. Sixty years after harvest, Deal and Tappeiner (2002) detected no significant changes between uncut and partially cut stands in tree species composition and stand structure. Further, the species richness and community structure of understory plants were similar among uncut and partially cut plots, although stands in which more than 50% of the basal area had been cut had significantly different plant community structure. Other elements of forest structure that have received attention are gap size and dynamics (Coates and Burton 1997, Ott and Juday 2002), the relation between gaps and tree species diversity (Coates and Burton 1997), structural and compositional diversity (Wardman and Schmidt 1998), and small mammal communities (Gitzen and West 2002).

4.3. Functional Diversity

Few published studies have specifically investigated functional diversity associated with different silvicultural systems (Appendix 2). In British Columbia, Marshall (2000) focused on nutrient cycling, which involves most of the soil biota, and nitrogen fixation because nitrogen (N) is often a limiting factor in PNW forests. Marshall (2000) reviewed the literature to report the response of various taxa (rotifers, protozoans, arthropods, bacteria, annelids, etc.) to clearcut, shelterwood, and a modified group selection. The only soil organisms studied in association with uneven-age regeneration methods are nematodes. Prescott (1997) investigated decomposition and N mineralization in an unreplicated study on Vancouver Island, British Columbia, and reported that the decomposition of needle litter was faster in the uncut, old-growth stand than in the units that received patch, shelterwood, and green-tree treatments. No significant differences in N concentrations were measured among the treatments (Prescott 1997).

4.4. Aquatic Resources

Most published research on aquatic resources focuses on physical elements like water, wood, and sediment (Harr 1980, Beschta et al. 2000). In recent years, studies have also included biological elements such as aquatic vertebrates and macro-invertebrates (Gregory 1997, Kauffmann et al. 2001, Olson et al. 2002) as research on riparian ecology has increased (Cunningham 2002). The link between terrestrial forest ecosystems and aquatic ecosystems is the riparian zone, which exists on a continuum from headwaters to estuaries (Kauffman et al. 2001). It appears that differences in headwater assemblages of both vertebrates and invertebrates exist longitudinally with stream flow gradients and latitudinally from streams (Olson et al. 2002). Despite the importance of riparian zones for fish and wildlife, data on the dynamics of riparian forests, their role in larger landscapes, and their responses to silvicultural treatments are limited (Bisson et al. 2002, Wipfli et al. 2003).

Research on silvicultural treatments and riparian ecosystems has focused on clearcutting in forested areas outside the riparian zone, rather than on direct treatment of riparian vegetation (Cunningham 2002). Controversy exists about the influence of clearcutting on peak flows at both the watershed and headwater scale. Beschta et al. (2000) focused on large peak flow events at watershed (60 to 101 ha) and at basin (62 to 640 km^2) scales because these flows are important, both ecologically for fish habitat, water quality, and riparian vegetation and physically for sediment transport and channel morphology. They did not find strong evidence for peak flow increases on large basins associated with clearcutting. Evidence for treatments other than clearcutting is limited (Appendix 2) despite decreasing emphasis on this silvicultural system in the PNW. One study, with 13 sites in western Oregon, varies riparian buffer widths and density management treatments (Olson et al. 2002). Initial reports describe predicted wood volume associated with the treatments and effects on aquatic vertebrates and invertebrates (Olson et al. 2002). Data on the effects of silvicultural treatments on aquatic resources are limited, but information is available on stream dynamics, fish communities, and species richness in the PNW (Reeves et al. 1998).

4.5. Wood

Estimates of wood quality or volume (Barbour et al. 2002, Busing and Garman 2002) and net revenues (Hummel et al. 2001, Marzluff et al. 2002,) associated with silvicultural treatments designed to enhance wildlife habitat (Bull et al. 1995) via retention of structural diversity (Weigand and Burditt 1992) are derived either from simulation (Barbour et al. 1997, Busing and Garman 2002, Cissel et al. 2002) or from retrospective studies (Barbour et al. 2002), but not from designed experiments (Appendix 2). Instead, computer models are being used to predict the potential effects of different silvicultural treatments on stand structure and wood quality (Busing and Garman 2002), but this opportunity is limited by the applicability of available models (Monserud 2003). Models can provide insight into relative differences associated with the spatial and temporal application of silvicultural treatments over landscapes comprising many stands (Hummel et al. 2002, Spies and Johnson 2003, Swanson et al. 2003); however, model development requires data from well-designed field studies measured on spatial and temporal scales relevant to the variable of interest. Estimates of variation in response variables are also important because they will differ by forest type, season, location, and other factors.

5. Discussion

Silvicultural treatments can be used to manipulate the structure and composition of forests to achieve specific objectives. As such, silviculture has an important role in forest management, whether the objective is increased compatibility among resources, site restoration, or wood production. Effective forest management—accomplishing objectives with minimum cost—requires information about the responses of various biotic and abiotic ecosystem elements to silvicultural treatments. This information is commonly a mixture of operational results, observational studies, and designed experiments. The weight given to these various sources of information depends on forest management objectives, on the legal and financial obligations of different forest owners and users, and on social values (Donoghue 2003). For example, a family managing a 30-ha forest will obtain and use information differently than an industrial or public forest owner with many thousands of hectares under management. In the PNW, most forest is publicly owned (Haynes et al. 2003), which means that setting objectives and evaluating information is subject to public review and comment. In this context, empirical data are often given greater weight in decisionmaking than knowledge obtained from other sources.

In the PNW, empirical data are currently insufficient to evaluate whether silvicultural treatments that create diversity in forest structure and composition conserve biodiversity. Data from experiments that examine the relation of forest structures and plant composition to biodiversity, aquatic resources, and wood production in association with silvicultural treatments are lacking for spatial scales larger than 100 ha (Appendix 2). Further, it is difficult to compare data from smaller scale studies because of differences in the (1) silvicultural treatments applied, (2) forest types studied, and (3) response variables measured. Few studies report on wood removals associated with silvicultural treatments, and even fewer discuss the costs of their implementation. Pre- and post-treatment basal area, species composition, and density of trees and snags are sometimes given, but information on the volume and value of wood removed is not. Data on the species richness of small mammals, understory vegetation, and birds provide a mixed picture of treatment effects for each stage of forest development. It may be that more studies are needed or perhaps species richness needs to be augmented with other diversity indices to measure biodiversity in meaningful ways (Reeves et al. 1998) and at meaningful spatial scales (He et al. 2002). Potential latitudinal and longitudinal effects on species richness (Olson et al. 2001) suggest that differences in biodiversity may exist independent of treatment effect among forests in the northern (Alaska) and southern (SW Oregon) extremes of the PNW and forests of coastal (Coast Range) and inland mountains (Cascade Range). Studies that characterize outcomes associated with different silvicultural treatments over areas comprising multiple stand types are needed to measure and interpret effects over time.

Despite a lack of empirical data from long-term studies relating specific silvicultural treatments to compatible forest management objectives in the PNW, both observation and simulation suggest that a mixture of forest development stages is important for conserving biodiversity (Chambers et al. 1999, Spies and Johnson 2003). Insight into patterns associated with the spatial and temporal application of silvicultural treatments over landscapes (Hummel et al. 2002, Spies and Johnson 2003, Swanson et al. 2003) may come from hybrid models (Monserud 2003), which together with growth and yield models can help generate testable hypotheses and guide management decisions. Additional data are necessary to identify the ranges in forest structure and composition desired at various geographic scales to accomplish specific management objectives. This is important because managing structure and composition at fine scales can be expensive, and managing them at coarse scales can create multijurisdiction ownership issues (Spies and Johnson 2003). In the 19th century, rectilinear surveys were adopted in the United States and Canada (Kain and Baigent 1992) instead of watersheds (Powell 1879) to demarcate ownership; this geometric legacy affects 21st century forest management. Square parcels governed by different laws and managed for different objectives often fragment watersheds in the PNW.

The methods used to manage structural and compositional diversity depend on site-specific conditions as well as on management objectives. For example, thinning is one silvicultural technique applied in various ways and for various objectives. It is not a new technique, yet it is being done in new ways because forest management objectives in the PNW are changing, particularly on public land. By targeting specific diameter classes or strata, thinning can be used to alter wildfire behavior (Agee 1996, Graham et al. 1999), to recruit specific understory plants (Kerns et al. 2003), to provide thermal cover (Smith and Long 1987, McTague and Patton 1989), and to grow trees with specific characteristics for wildlife habitat (Ferguson and Archibald 2001). Although contemporary practices like variable-density thinning do not have the benefit of long-term data supporting their intensity or design, they do rely on established theories of plant ecology and size-density relations. Further, extensive silvical information on the shade tolerance and growth form of various PNW species can be used to predict responses of mixed-species stands to various types and intensities of thinning. Current knowledge may be adequate, depending on the particular objective and the scale at which it is manifested. At the tree level, for example, if large branches and deep crowns are desired, then tree density should be lower than if small knot size is the goal. In contrast, wildfire (Agee 1993) and large carnivore (Ruggiero et al. 1994) home ranges generally occur at spatial scales larger than a stand in PNW temperate rainforests, and knowledge about within- and between-stand variation in forest structure and composition relate to organisms or to phenomena occurring across multiple stands is limited (DeStefano 2002).

Diversity rather than simplicity in forest structure and composition is not a new target condition (Gayer 1886, Matthews 1989, James 1996, Lähde et al. 1999, O'Hara 2001), nor is the concept of maintaining continuous forest cover (Schütz 2002, Heitzman 2003). However, these concepts are just beginning to be adapted to PNW forests, as an outcome of regional economic and demographic change. In the 19th and 20th centuries, the PNW was a frontier, and prosperity and a continued timber supply were challenges of the time. It was believed that the way to meet these challenges was to convert structurally and compositionally diverse forests to regulated, uniform stands of commercially valuable Douglas-fir trees. In contrast, at the beginning of the 21st century the PNW is no longer a frontier. Diversity in structure and composition is now part of regional forest management objectives, but both the scale at which this diversity should be determined and the way it should be managed remains unclear. Increased clarity in the range and pattern of conditions desired over time, combined with site-specific information, will help silviculturists translate the concept of diversity into a system of treatments that support increased compatibility among forest resources.

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Appendix 1. List of species used in text.

Common name	**Latin name**
Plants	
Alaska cedar	*Chamaecyparis nootkatensis* (D. Don) Spach
Bigleaf maple	*Acer macrophyllum* Pursh
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Grand fir	*Abies grandis* (Dougl. ex D. Don) Lindl.
Lodgepole pine	*Pinus contorta* Dougl. ex Loud.
Oregon white oak	*Quercus garryana* Dougl. ex Hook.
Pacific silver fir	*Abies amabilis* Dougl. ex Forbes
Ponderosa pine	*Pinus ponderosa* Dougl. ex Laws.
Red alder	*Alnus rubra* Bong.
Salal	*Gaultheria shallon* Pursh
Sitka spruce	*Picea sitchensis* (Bong.) Carr.
Vine maple	*Acer circinatum* Pursh
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg
Western larch	*Larix occidentalis* Nutt.
Western redcedar	*Thuja plicata* Donn ex D. Don
Animals	
Brown-headed cowbird	*Molothrus ater*
Northern spotted owl	*Strix occidentalis caurina*
Red squirrel	*Tamiasciurus hudsonicus*

Appendix 2. Silvicultural studies from the temperate coastal rainforest region of North America that include response variables other than (or in addition to) wood.

Citation	**Region[1]**	**Study type[2]**	**Size (and total number of treated units)**	**Silvicultural treatment[3]**	**Response variable(s)[4]**
Bailey et al. 1998	OCA, OCR (c)	OBS	>10 ha (80)	Thinned from below	Cover, abundance, and species richness of understory vascular plants
Battles et al. 2001	SONC (b)	OBS	<0.1-8 ha (16)	Clearcut, shelterwood, group selection, single tree selection	Species richness of understory vascular plants
Beese and Bryant 1999	BC (b)	DE (3)	8.6-69 ha (11)	Shelterwood, patch clearcut, green-tree retention	Cover, frequency and number of understory plant species; breeding bird species richness and abundance
Beschta et al. 2000	OCA (b)	OBS	60 ha-640 km (2)	Clearcut and broadcast burn, with and without road construction	Peakflow

Appendix 2. Silvicultural studies from the temperate coastal rainforest region of North America that include response variables other than (or in addition to) wood (continued).

Citation	**Region**[1]	**Study type**[2]	**Size (and total number of treated units)**	**Silvicultural treatment**[3]	**Response variable(s)**[4]
Buermeyer and Harrington 2002	WCA (a)	OBS	15 ha (1)	Clearcut with reserves	Overstory tree mortality and conifer regeneration
Bull et al. 1995	BM (a)	OBS	15-22 ha (2)	Thinned from below	Abundance of birds, ants, dead wood; timber volume and value
Busing and Garman 2002	OCA (b)	SIM	Not applicable	Clearcut, thinning from below	Wood volume and quality, canopy height diversity
Carey 2001	WCO (b)	DE (4)	13 ha (16)	Variable density thinning	Squirrel abundance
Chambers and McComb 1997	OCR (b)	DE (3)	5-18 ha (12)	Group selection, green-tree, shelterwood	Abundance of wintering birds

Appendix 2. Silvicultural studies from the temperate coastal rainforest region of North America that include response variables other than (or in addition to) wood (continued).

Citation	**Region**[1]	**Study type**[2]	**Size (and total number of treated units)**	**Silvicultural treatment**[3]	**Response variable(s)**[4]
Chambers et al. 1997, 1999	OCR (b)	DE (3)	5.5-17.8 ha (29)	Group selection, green-tree, shelterwood	Abundance of breeding birds, cavity-nesting birds, condition and use of artificially created snags
Cole et al. 1998	OCR (c)	DE (3)	8-12 ha (9)	Clearcut; clearcut and bum; clearcut, burn and glyphosate	Small mammal capture rates
Deal and Tappeiner 2002	AK (c)	OBS	10 ha (18)	Partial cutting	Species composition and richness, tree cohorts and growth, and understory vascular plants in Sitka spruce/western hemlock forest

Appendix 2. Silvicultural studies from the temperate coastal rainforest region of North America that include response variables other than (or in addition to) wood (continued).

Citation	**Region**[1]	**Study type**[2]	**Size (and total number of treated units)**	**Silvicultural treatment**[3]	**Response variable(s)**[4]
Gitzen and West 2002	WCA (b)	OBS	38-1963 m^2 (33)	Experimental gap	Abundance, persistence, and occurrence of small mammals
Hagar et al. 1996	OCR (c)	OBS	65-510 ha (16)	Thinned from below	Abundance and diversity of breeding and wintering birds
Halpern and McKenzie 2001	WCA, SONC (d)	DE (6)	13 ha (24)	Aggregated retention, dispersed retention	Ground cover, slash depth, woody debris
Harr 1980	OCA (b)	OBS	59-253 ha (3)	Clearcut and road construction	Peakflow
Mitchell 2001	BC (b)	DE (3)	9 ha (12)	Clearcut, patch cut, green tree, shelterwood	Foliage morphology and physiology of planting seedlings

Appendix 2. Silvicultural studies from the temperate coastal rainforest region of North America that include response variables other than (or in addition to) wood (continued).

Citation	**Region[1]**	**Study type[2]**	**Size (and total number of treated units)**	**Silvicultural treatment[3]**	**Response variable(s)[4]**
Olson et al. 2002	OCR (c)	OBS	Variable width stream buffers (6-126 m (13)	Variable retention thinning	Aquatic vertebrates and macroinvertebrates, microsite conditions, estimated wood volume
Prescott 1997	BC (b)	DE (3)	>9 ha (9)	Patch cut, green-tree retention, shelterwood	Litter decomposition and nitrogen mineralization
Schowalter 1995	OCA (b)	OBS	10-25 ha (24)	Partial cutting; clearcut	Canopy arthropod population intensities and herbivory
Weigand and Burditt 1992	OCA (b)	OBS	7-33 ha (4)	Structural (green-tree) retention	Net potential merchantable volume, net potential lumber value
Wolff and Zasada 1975	AK (a)	OBS	1-2.4 ha (8)	Clearcut, shelterwood	Red squirrel (*Tamiasciurus hudsonicus*) middens

Appendix 2. Silvicultural studies from the temperate coastal rainforest region of North America that include response variables other than (or in addition to) wood (continued).

[1] Region: AK= Alaska; BC = British Columbia: BM = Blue Mountains (eastern Oregon); OCA = Oregon Cascade Range; OCR = Oregon Coast Range; SONC = southern Oregon/northern California; WCA= Washington Cascade Range; WCO = Washington Coast/Olympic Peninsula. a = one location, b = more than one location within a geographically restricted area (e.g., an experimental forest), c = multiple locations within part of a region, and d = several locations distributed across one or more regions.
[2] Study type: DE = designed experiment (uses standard statistical principles (e.g., randomization) for scientific experimentation (see Hinkelmann and Kempthome 1994 for discussion)). Number of replicates given in parentheses. OBS = observational study (not a designed experiment); SIM = treatments "applied" using computer simulation.
[3] Silvicultural treatment: refer to the accompanying text for descriptions and definitions of treatments. Simulation (SIM) studies "apply" treatments using computer simulation.
[4] Response variables: Studies that include only wood quality or volume as response variables are not included.