The Focus of Intensive Silvicultural Research on Coastal Douglas-Fir Over the Last 20 Years

Andrew Moores, Klaus Puettmann, and Doug Maguire

ABSTRACT

Silvicultural regimes are becoming more intensive in the US Pacific Northwest, incorporating a multitude of treatments over the length of the rotation. Therefore, there is a need to understand not only how individual treatments affect forest productivity, but also how these treatments interact to determine productivity. To help launch the Planted Forest Productivity and Value Enhancement Program at Oregon State University, an extensive literature search was conducted over 9 different classes of silvicultural treatments and 10 different categories of measured responses. The objective was to examine the scope of our current knowledge base about intensive silvicultural practices in the Pacific Northwest, particularly the mechanisms by which various treatment combinations or regimes control the productivity of coastal Douglas-fir stands. The literature, 1984 through 2004, shows that studies were more likely to focus on a combination of silvicultural treatments or practices if they were applied during similar times of stand development. Very little documented research addressed the interactive effects of treatments applied sequentially over the rotation. Although most studies monitored growth, yield, and tree mortality, fewer studies investigated environmental, physiological, and morphological responses that are key to understanding and predicting how both tested and untested silvicultural regimes will affect forest productivity.

Keywords: literature review, intensive forestry, forest productivity

Research programs addressing intensive plantation management for timber production traditionally have focused on a single silvicultural treatment or class of treatments, such as tree breeding, nursery seedling production, vegetation control, or density management. Likewise, monitored responses have most commonly been limited to stem volume growth and tree mortality. Although stemwood production may be the primary goal, it is dependent on a web of complex interactions between silvicultural treatments, genotypes, physiological processes, and the above- and belowground environment (Rousseau et al. 2005). In particular, the processes that underlie stemwood growth response to various silvicultural treatments have received scant coverage. Field trials that will explicitly address combinations of silvicultural manipulations at radically different times in the rotation have been initiated only recently (Chapell et al. 1988). Regardless, field trials cannot be established for every possible combination of treatments, and forest managers can not wait for these field trials to fully mature before making decisions about current manipulations. Even if they could wait, the results may no longer be applicable under future growing conditions. A more thorough understanding of key processes and key elements of stand structure would enhance our capacity for interpolating between tested regimes and extrapolating to untested ones. A stronger information base and subsequent enhancement of management efficiency are widely recognized as critical to ensuring a vibrant forest industry in the Pacific Northwest. Numerous forums over recent years have confirmed this view and have recognized the need to accelerate research capacity in various facets of intensive plantation management.[1]

The general lack of integration among disciplines and silvicultural practices can be attributed primarily to the compartmentalized nature of research cooperatives and to the relatively narrow focus of research programs developed by individual scientists or relatively small teams. To understand the scope and depth of the current information base on intensive silvicultural practices, including responses to the full range of treatments and treatment combinations, a systematic literature search and conceptual synthesis were needed. Through the Planted Forest Initiative (PFI) at Oregon State University, the following three products were established as a goal: (1) an electronic catalog of literature from the Pacific Northwest; (2) a summary of treatment responses in silvicultural field trials; and (3) an interpretive synthesis of tree, stand, and ecosystem responses to silvicultural manipulation. Electronic access to currently available information was recognized also as essential for its wide application by many landowners, foresters, and researchers.

This article summarizes the focus and extent of intensive silvicultural research covering coastal Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco var. *menziesii*) in the Pacific Northwest. Specific objectives were (1) to assess time trends in intensive silvicultural research activity over the past 20 years; (2) to summarize the amount of literature available for different classes of silvicultural treatments; (3) to identify experiments testing various combinations of silvicultural treatments; (4) to catalog the types of responses being measured in silvicultural field trials; and (5) to cross-classify the literature by silvicultural treatment and monitored responses.

Methods

The literature search was conducted in the CAB Abstracts database (1997–2000, SilverPlatter Information N.V.) in May 2005. CAB Abstracts is a web-based searchable bibliographic database,

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Table 1. Search words for species and geographical range applied in the literature search conducted in CAB Abstracts.

Species	Douglas-fir (*P. menziesii*)
Geographical range	British Columbia, Oregon, Pacific Northwest, Washington (TI, AB, GE, or BT)

Abbreviations for the following fields in CAB Abstracts: TI, title field; AB, abstract field; GE, geographic headings field; BT, broad terms field.

covering the applied life sciences (CABI Publishing 2006). It contains publications from 1984 to the present, and although CAB Abstracts does not cover all outlets, it does contain all major forestry journals. Our search was restricted to publications covering the past 20 years primarily because of limited electronic access before 1984. This time frame, however, also covers an important period of globalization in the forest products industry and transitions in private forest ownership and land-use patterns in the Pacific Northwest, from primarily large industrial ownership to a much more fragmented land base and diversified ownership.

To systematize the literature search, four sets of search words were created. The first two sets of search words focused on species and geographical range, with concentration on coastal Douglas-fir in Oregon, Washington, and British Columbia (Table 1). Nine classes of silvicultural treatments or manipulations were selected: genetic tree improvement, nursery operations, planting operations, site preparation, release treatments, fertilization, thinning, pruning, and tree/stand protection. Search words within each class facilitated finer classification of the publications identified (Table 2). Ten response categories also were selected along with more detailed search words within each category. Basic responses included growth and yield, economics, wood quality, mycorrhizal structures, soil properties, carbon allocation, photosynthesis, tree and stand health, tree morphology and physiology, and tree phenology (Table 3).

Search word lists were refined through an iterative process to ensure that as many relevant publications as possible would be identified and, at the same time, prevent an unwieldy clutter of nonrelevant publications. Once a search was completed, the selected publications were examined for relevance to the subject class. Search words were eliminated or modified if they led to a large number of irrelevant publications. If nonrelevant publications were included in search results because of the appearance of an otherwise effective search word in one specific field, then that search word was limited to more appropriate fields within CAB Abstracts (e.g., the title, abstract, and descriptor fields).

Publications were assigned to the tree/stand protection class if the study included silvicultural treatments implemented with the purpose of studying their effect on abiotic or biotic threats or on tree and stand responses to these threats. This class included publications covering treatments aimed directly at protecting a seedling, tree, or whole stand (e.g., insecticide spraying). It also included publications from other silvicultural classes such as thinning or genetic selection, when these treatments were assessed for their effectiveness in tree or stand protection. Therefore, we included publications in the tree/stand protection class if they contained either a direct treatment search word or a search word from one of the other eight silvicultural classes along with a search word implying an abiotic or biotic threat (see Table 2 for a list of threat search words).

A database of silvicultural literature was created in Endnote version 7 (1988–2003; Thomson ISI, Philadelphia, PA). This database originally included all records from CAB Abstracts with at least one word from each of the four sets of search words—geographical location, subject species, silvicultural treatment, and measured response. The abstract from each record was then reviewed for relevance to intensive silviculture of coastal Douglas-fir. A record was discarded from the database if the corresponding publication was deemed irrelevant or if it dealt exclusively with interior Douglas-fir (*P. menziesii* var. *glauca* [Beissn.] Franco). Abstracts of the remaining publications were examined closely to determine the specific silvicultural treatments that were implemented and the tree, stand, and site responses that were measured. This information was condensed into a set of keywords, which was added to the publication's record in Endnote. Subsequent investigations were based on these keywords in the revised database, hereafter referred to as the PFI database.

The number of publications was plotted for each of the last 21 years to portray temporal trends in intensive silvicultural research. Because of the lag between time of publication and its appearance in CAB Abstracts, publications from 2004 were not included in this analysis. A review of previous years showed that only about one-half of all publications were included in CAB Abstracts during the year the journal issue was published. Because the CAB Abstract searches were conducted in the spring of 2005, they were not likely to be representative of the actual number of publications in 2004.

From the PFI database, we tallied the total number of publications for each silvicultural treatment class and each response category. For each treatment class, we determined the number of publications that investigated that particular class of treatments exclusively. For each possible pair of treatment classes, we then determined the number of publications that incorporated both classes of treatments. Records were then cross-classified by treatment and response to better understand the types of responses that were monitored for each type of silvicultural treatment.

Finally, we targeted two higher-order treatment combinations that are currently of special interest to practitioners of intensive plantation management in the Pacific Northwest: (1) genetic tree improvement × planting × release treatment, and (2) genetic tree improvement × planting × release treatment × fertilization. The first treatment combination is exemplified by the Type IV/Genetic Improvement trials currently being implemented by the Stand Management Cooperative (Turnblom and Briggs 2004).

Results and Discussion

Overall Research Activity and Temporal Trends

The PFI database contained 671 publications for the 20-year period, indicating a substantial level of research on plantation silviculture in coastal Douglas-fir over its native range. The actual number of publications is almost certainly a bit higher than what we report here because electronic literature searches (such as those available through CAB Abstracts) have been shown to have inherent flaws and rarely find all possible citations (Valiela and Martinetto 2005). However, the overall range and trends still should be representative.

Despite the large number of publications identified, the level of research and publishing activity was not constant over time. A general decline in the amount of relevant literature was observed over the last 20 years, despite tremendous variation from year to year (Figure 1). The average annual publication rate between 1984 and 2003 was approximately 30 publications per year. The 5-year periodic annual rate decreased, however, from 38 publications per year for 1984–1988 to 19 publications per year for 1999–2003. This

Table 2. Search words for classes of silvicultural treatments and for more specific treatments within those classes.

Class of silvicultural treatment	Silvicultural treatments and techniques
Genetic tree improvement	Breeding (program OR programmes OR programs), early selection, [(early testing) AND (genetic OR genetics)], genetic control, genetic improvement, genetic manipulation, genetic regulation, genetic selection, genetic tree improvement, genetic variation, orchard management, progeny (test OR testing OR tests OR trial OR trials), seed (orchard OR orchards), [(seed production) AND (genetic OR genetics)], tree breeding, tree improvement
Nursery operations	Cold storage, container grown, culling, nurseries, nursery, seedling production, sowing, transplant, transplanted
Planting operations	Initial (density OR densities), outplanting, planting (density OR densities), planting (site OR sites), planting stock, reforestation, spacing, [stand (density OR densities) AND (planting OR planted)], underplanting
Site preparation	[Bedding NOT animal], broadcast burn, chemical preparation, mechanical preparation, mechanical treatment, pile and burn, prescribed (burn OR burning), prescribed fire, ripping, scarification, scarified, site preparation
Release treatments	Brush competition, chemical release, manual release, manual (treatment OR treatments), mechanical release, release (treatment OR treatments) {[Chemical (application OR applications), chemical (treatment OR treatments), herbicide, herbicides, vegetation control, vegetation management, weed control] NOT [site preparation search word]}
Fertilization	Ammonium nitrate application, fertilization, fertilize, fertilized, fertilizer, fertilizers, (N OR nitrogen) application, urea application
Thinning	Density management, respacing, [stand density NOT (planting OR planted)], thin, thinned, thinning
Pruning	[Prune NOT (self prune)], [pruning NOT (self pruning)]
Tree/stand protection	Animal (barrier OR barriers), animal control, animal damage control, biological control, disease (control OR management), fencing, fungicide, fungicides, insecticide, insecticides, integrated control, pathogen (control OR management), pest (control OR management), [pesticide in (TI, AB, DE)], [pesticides in (TI, AB, DE)], physical (barrier OR barriers), tubing, viricide, viricides, [(cold hardiness, cold resistance, cold tolerance, *Cylindrocarpon*, drought hardiness, drought resistance, drought tolerance, forest pests, *Fusarium*, *Leptographium wageneri*, *Phaeocryptopus gaeumannii*, *Phellinus weirii*, root disease, root rot, Swiss Needle Cast) AND (treatment search word from one of the other eight intensive silvicultural treatment classes)]

Abbreviations for the following fields in CAB Abstracts: TI, title field; AB, abstract field; DE, descriptors field.

Table 3. Search words for 10 categories of tree and stand responses to intensive silviculture and for specific responses monitored.

Response category	Specific responses
Carbon allocation	(Aboveground OR above ground) allocation, allocation of photosynthate, (belowground OR below ground) allocation, biomass allocation, (branch to foliage OR branch-foliage) allocation, carbon allocation, (crown-to-stem OR crown-stem) allocation, (foliar OR foliage OR growth) efficiency, growth allocation, photosynthetic allocation, root shoot (ratio OR ratios), root to shoot (ratio OR ratios)
Economics	Cash, cost, costs, (discount OR discounted) rate, (discount OR discounted) value, economic in (AB, TI, DE), economics, financial, income, incomes, interest (rate or rates), investment, net value, net worth, present value present worth, (rate OR rates) of return
Growth and yield	(Aboveground OR above ground) biomass, (aboveground OR above ground) growth, above ground (production OR productivity), aboveground (production OR productivity), annual growth, basal area growth, biomass growth, bole growth, diameter NOT {[height diameter (ratio OR ratios)] OR [H/D (ratio OR ratios)]}, growth (response OR responses), height NOT {[height diameter (ratio OR ratios)] OR [H/D (ratio OR ratios)]}, heights NOT {[height diameter (ratio OR ratios)] OR [H/D (ratio OR ratios)]}, increment, increments, primary (production OR productivity), radial growth, sapling growth, seedling growth, stand biomass, stand growth, stem growth, tree biomass, tree growth, volume, volumes, yield NOT (financial OR economic), yields NOT (financial OR economic)
Mycorrhizal response	Ectomycorrhiza, ectomycorrhizae, ectomycorrhizal, ectomycorrhizas, mycorrhiza, mycorrhizae, mycorrhizal, mycorrhizas in (TI, AB, DE)
Photosynthesis	Chlorophyll, photosynthesis, photosynthetic (rate OR rates OR response OR responses OR efficiency) Soil Properties CEC, C/N (NOT in AU), carbon nitrogen (ratio OR ratios), carbon to nitrogen (ratio OR ratios), cation exchange capacity, exchangeable (cation OR cations), (N OR nitrogen OR nutrient) availability, (N OR nitrogen OR nutrient) capital, (N OR nitrogen OR nutrient) cycling, (N OR nitrogen OR nutrient) leaching, (N OR nitrogen) mineralization, nitrification, SOC, soil (bacteria OR bacterium), soil (C OR carbon), soil (characteristic OR characteristics), soil (microbes OR microbial), soil moisture, soil (N OR nitrogen), soil organic (C OR carbon), soil organic matter, soil (organism OR organisms), soil pH, soil porosity, soil (property OR properties), soil respiration, soil temperature, soil water, water availability
Tree morphology	Crown length, crown ratio, foliar (N OR nitrogen), (foliar OR leaf) and Physiology nutrient, H/D (ratio OR ratios), height diameter (ratio OR ratios), leaf area, leaf (N OR nitrogen), leaf water potential, plant morphology, plant physiology, projected (shoot OR root OR crown) area, projection area, root (architecture OR development), root (density OR length density), root growth (capacity OR potential), stomatal conductance, xylem (potential OR water potential)
Tree phenology	Bud break, budbreak, bud burst, budburst, bud development, bud flush, budflush, bud set, budset, dormancy, phenological, phenology
Tree and stand health	Damage in (TI, AB, DE), defoliation, disease incidence, disease infection, disease prevalence, disease resistance, disease symptoms, disease tolerance, (forest OR stand OR tree) health, incidence of disease, incidence of infection, injury, injuries, mortality, needle (discoloration OR discolouration), needle retention, rate of infection, survival, susceptibility, vigor, vigour
Wood quality	Branch growth, branch size, branch (trait OR traits), branching (trait OR traits), crown wood, crownwood, earlywood, epicormic (branch OR branches OR branching), (fiber OR fibre) length, (fibril OR microfibril) angle, forking, juvenile wood, knot, knots, latewood, log (grade OR grades), lumber (grade OR grades), lumber strength, mature wood, pulp quality, sinuosity, specific gravity, wood characteristics, wood density, wood (property OR properties), wood quality, wood strength

Abbreviations for the following fields in CAB Abstracts: TI, title field; AU, author field; AB, abstract field; DE, descriptors field.

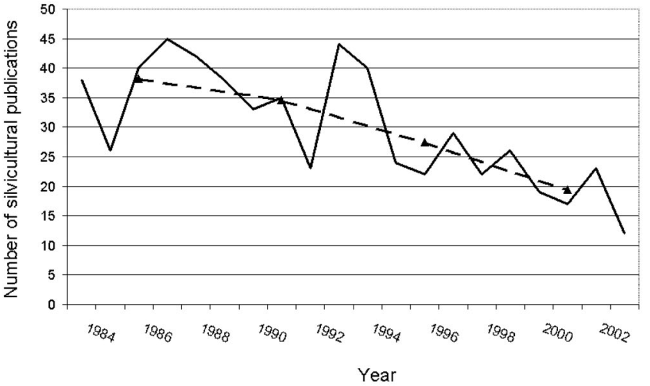

Figure 1. Number of publications in CAB Abstracts addressing plantation silviculture of Douglas-fir stands from1984 to 2003. The dashed line joins points representing the average number of publications for the following 5-year intervals: 1984–1988, 1989–1993, 1994–1998, and 1999–2004; points are plotted on the midpoint of the interval.

trend is the result of many factors, the most important being a shift in research priorities from timber growth to other forest uses for both the US Forest Service and the university forestry programs (Wallinger 2005). Many forestlands also have been transferred from vertically integrated forest products companies to Timber Investment Management Organizations (TIMOs) over the last 10 years (Wallinger 2005). These TIMOs have placed a lower priority on research funding as previous forest landowners, and many forest products companies have terminated or dramatically reduced their forest research programs. The future of other research units within the forest products industry remains tenuous as the various companies continue to divest their timberlands (Wallinger 2005).

Silvicultural Treatments

The strongest emphasis in the published literature has been on tree and stand protection, thinning, fertilization, and nursery operations, with less emphasis on pruning and site preparation (Table 4). Research trends over the last 15 years showed variable correspondence with management trends, even after accounting for the typical time lag between identification of a research need, implementation of the research, and publication of the results. Several plausible scenarios could lead to these different relationships between research activity and silvicultural operations. For example, a close parallel in activities, perhaps with a slight time lag, would be expected if the operational frequency first increased and then raised questions about optimal implementation of that particular silvicultural treatment. Alternatively, a technological development may first stimulate a temporary surge in research activity, followed by a gradual increase in the operational use of new or improved silvicultural techniques. The acreage of forestlands receiving site preparation, as reported in the University of Washington Stand Management Cooperative's 2001 survey of actual and anticipated silvicultural practices of its members (Briggs and Trobaugh 2001), generally paralleled the volume of research in the PFI database on site preparation during this same time period. Specifically, the decline in research on mechanical preparation and prescribed fire over the last 10 years closely tracked the declining use of mechanical site preparation (Figure 2) and broadcast burning over the same period (Briggs and Trobaugh 2001). Likewise, the increase in research publications on chemical site preparation over the last 10 years corresponded closely to the increased use of preemergent herbicides from 1991 through 2001. In contrast, a fairly constant decline in research publications covering fertilization over the last 20 years accompanied an increase in the proportion of acres being fertilized through the 1990s (Briggs and Trobaugh [2001]; Figure 3). This increase, primarily in nitrogen fertilization, coupled with a decrease in research activity, is especially noteworthy for at least three reasons: (1) the extreme variability in growth response to fertilization is still poorly understood; (2) the cost of fertilizer has increased significantly; and (3) high foliar nitrogen is correlated with Swiss Needle Cast severity, suggesting that excess nitrogen may predispose Douglas-fir to the disease (El-Hajj et al. 2004, Talbert and Marshall 2005).

Combinations of Treatment Classes

For some treatment classes, research was most often focused exclusively on single silvicultural practices within that class, while for other treatments, research was more often conducted in combination with those of another class (Table 4). At one extreme, 64% of all release studies focused exclusively on release treatments, whereas at the other extreme, only 32% of the publications on tree and stand protection focused exclusively on treatments in that class. The low percentage of publications focusing exclusively on tree and stand protection, however, reflects, in part, the difference in how we defined this particular class as a silvicultural treatment, allowing any of the other eight treatment classes to simultaneously be considered as a tree/stand protection treatment depending on the context or motivation for treatment.

Combinations of silvicultural treatments that typically are applied during the same stage of stand development were more often designed into a single study than combinations of treatments that are more usually applied at widely separated times in the rotation. Hence, studies that investigated treatment combinations tended to concentrate either on intermediate treatments (e.g., thinning and fertilization) or on stand establishment treatments (e.g., genetic tree improvement, nursery operations, release treatments, and site preparation; Table 4). However, stand establishment and young stand tending treatments were combined much less frequently with later intermediate treatments, most likely because of the longer study duration required and the compartmentalized nature of intensive silvicultural research. The exception to this pattern was initial spacing as a planting operation. This practice was commonly investigated in combination with thinning, fertilization, and pruning treatments, most likely because initial density will have a direct impact on the need for and timing of future precommercial thinning and pruning operations. This paucity of long-term, integrative, silvicultural research projects is not unique to Douglas-fir in the Pacific Northwest. Vegetation management researchers in Canada, e.g., have called for field trials that test integrative silvicultural regimes incorporating multiple treatments applied both concurrently and successively through the rotation, so they can assess the impacts of vegetation control over an entire rotation cycle (Thompson and Pitt 2003).

The knowledge gap associated with complex silvicultural regimes involving innumerable treatment schedules has led to a limited capacity for predicting the outcomes of these regimes. Silvicultural information from combined data sets and those from more complex studies often is embodied in growth models as a concise representation of our current state of knowledge. Literature documenting these models was not included in the literature search. Although some publications on growth model components would qualify as

Table 4. Number of records for each class of silvicultural treatment in the coastal Douglas-fir from 1984 to 2004, cross-classified by pairwise treatment class combinations.

	Genetic tree imprvmnt.	Nursery oper.	Site prep.	Planting oper.	Release trmts.	Fert.	Thinning	Pruning	Tree/stand protection
Genetic tree imprvmnt.	***50***	13	3	4	2	1	1	1	21
Nursery oper.	13	***79***	3	9	6	8	2	1	32
Site prep.	3	3	***18***	13	14	6	6	1	12
Planting oper.	4	9	13	***38***	14	14	20	5	18
Release trmts.	2	6	14	14	***55***	9	6	1	7
Fert.	1	8	6	14	9	***67***	56	6	10
Thinning	1	2	6	20	6	56	***56***	9	18
Pruning	1	1	1	5	1	6	9	***9***	5
Tree/stand protection	21	32	12	18	7	10	18	5	***47***
Total	96	141	46	97	86	146	136	24	147

Bold and italicized numbers along the diagonal represent publications solely addressing that treatment class. The same record can contribute to more than one cell in the table; therefore, row and column totals exceed the actual number of publications.

Imprvmnt., improvement; fert., fertilization; oper., operations; prep., preparation; trmts. Treatments.

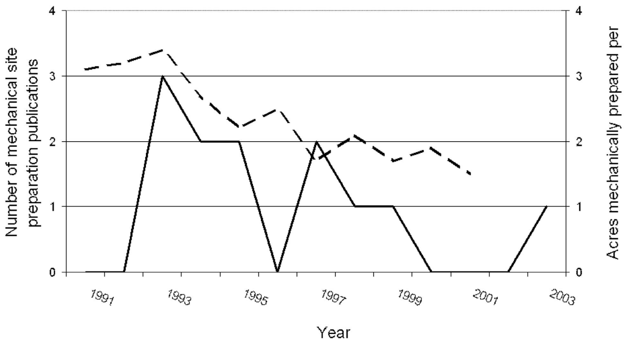

Figure 2. Number of publications in CAB Abstracts addressing mechanical site preparation of Douglas-fir stands from 1991 to 2003. The dashed line represents the number of acres mechanically prepared per 1,000 ac of net timberland among members of the University of Washington's Stand Management Cooperative from 1991 to 2001 (data taken from Briggs and Trobaugh 2001).

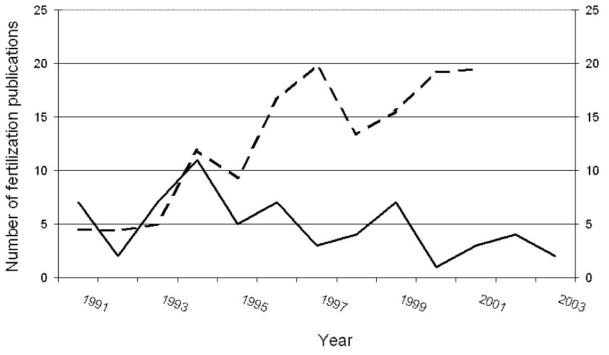

Figure 3. Number of publications in CAB Abstracts addressing fertilization of Douglas-fir stands from 1991 to 2003. The dashed line represents the number of acres fertilized per 1,000 ac of net timberland among members of the University of Washington's Stand Management Cooperative from 1991 to 2001 (data taken from Briggs and Trobaugh 2001).

analyses and interpretations of silvicultural field trials, model components that accommodate multiple silvicultural treatments and model simulations of untested treatment combinations often are simply gross extrapolations awaiting validation by strategically selected field trials.

The diversity of regional growth models (Ritchie 1999) and their widely divergent behavior reflect, in part, the lack of data covering the complex treatment regimes that they can simulate. The only comprehensive growth simulator for the region is the Forest Vegetation Simulator (FVS; Dixon 2002, USDA Forest Service 2005). This simulator relies on three separate models to project a stand from establishment through the end of the rotation: an establishment model, a small-tree model, and a large-tree model. The establishment model in the Pacific Northwest Coast and Westside Cascades Variants of FVS are capable of simulating the effects of prescribed fire, mechanical scarification, and initial planting density. The two subsequent models then allow for thinning, fertilization, pruning, and pest management at later ages. Other growth and yield simulators, such as Regional Vegetation Management Model (RVMM; RVMM Project 1998) and CONIFERS (Ritchie 2006), are built specifically to simulate early stand development and can simulate tree and stand response to vegetation management and precommercial thinning. A separate group of models is needed to forecast response to intermediate treatments and final yield at the end of the rotation. This latter group of models includes ORGANON (Hann 2003), DFSIM version 1.4 (Curtis et al. 1981), and TREELAB version 1.0 (Stand Management Cooperative 2004). Although these growth models can simulate the effects of fertilization and thinning, they are not capable of predicting a stand's response to alternative stand establishment treatments. Interactions between stand establishment practices (e.g., vegetation management and site preparation) and later silvicultural treatments (e.g., commercial thinning and fertilization) remain largely unpredicted.

Interaction effects attributable to the combination of genetic improvement and other silvicultural treatments are particularly problematic given the prevalence of genetically improved planting stock. Various first approximations have been proposed to represent genetic improvement in growth projections. Hamilton and Rehfeldt (1994) developed a method for estimating growth multipliers to incorporate genetic improvement into the Inland Empire Variant of FVS; however, this method required several assumptions or hypotheses about differences in stand development imposed by genetically improved stock, none of which were testable with available data.

The interaction of genetic improvement and other silvicultural treatments, such as vegetation management, has been investigated for other species in other regions, e.g., loblolly pine (*Pinus taeda* L.) in the southeastern United States (Martin and Shiver 2002), and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) in northern California (MacDonald et al. 1999). However, our search identified no long-term field trials that investigated this particular interaction between genetic improvement of coastal Douglas-fir and vegetation management. Two publications in the PFI database did address

Table 5. Number of records for each response category in the coastal Douglas-fir from 1984 to 2004 cross-classified by pairwise response combinations.

	Growth and yield	Economics	Wood quality	Tree and stand health	Soil properties	Tree morph. and phys.	Photosynthesis	Carbon allocation	Tree phenology	Mycorrhizal structures
Growth and yield	***62***	30	26	154	44	125	9	34	29	18
Economics	30	***18***	7	12	3	4	1	1	1	0
Wood quality	26	7	***12***	3	1	6	1	3	3	0
Tree and stand health	154	12	3	***52***	16	74	2	14	21	9
Soil properties	44	3	1	16	***24***	25	2	5	1	5
Tree morph. and phys.	125	4	6	74	25	***12***	12	27	23	6
Photosynthesis	9	1	1	2	2	12	***0***	1	2	1
Carbon allocation	34	1	3	14	5	27	1	***1***	4	3
Tree phenology	29	1	3	21	1	23	2	4	***2***	0
Mycorrhizal structures	18	0	0	9	5	6	1	3	0	***5***
Total	390	63	48	280	81	177	13	36	52	29

Bold and italicized numbers along the diagonal represent publications solely addressing that response category. The same record can contribute to more than one cell in the table; therefore, row and column totals exceed the actual number of publications.
Morph., morphology; phys., physiology.

both genetic tree improvement and release treatments, but one investigated only the effect of vegetation management on early selection efficiency in progeny testing (Woods et al. 1995), and the other only discussed genetic tree improvement as a possible alternative to vegetation management (McDonald and Fiddler 1993).

The two searches for higher-order treatment combinations (genetic tree improvement × planting × release treatment × fertilization and genetic tree improvement × planting × release treatment) confirmed the expected lack of integrative experimental work. Only a single publication addressed all four treatment classes, but it focused on the role of intensively managed Douglas-fir forests in the world timber market, with only a qualitative discussion of the positive effect of different silvicultural treatments (Hermann and Lavender 1999). A second publication did integrate three treatment classes in established field trials (genetic tree improvement × planting × release treatment). However, this publication, already mentioned previously, investigated the effect of vegetation management and close spacing on early selection efficiency in progeny tests (Woods et al. 1995).

Response Categories

As expected, broader response categories such as growth and yield, tree and stand health, and tree morphology and physiology were found with greater frequency in the literature, whereas more specific responses such as photosynthesis or mycorrhizal structure were less frequent (Table 5). Most publications included multiple response categories, even within the broader categories. Two hundred and twenty-five publications combined at least one commodity-orientated response (i.e., growth and yield, tree and stand health, economics, and wood quality) with a response involving ecological, physiological, or morphological mechanisms (i.e., photosynthesis, soil properties, carbon allocation, tree phenology, tree morphology and physiology, and mycorrhizal response). However, in total almost twice as many publications contained a response variable related to tree growth, value, and health compared with environmental, physiological, or morphological responses (566 or 84% of all PFI publications versus 292 or 44% of all PFI publications).

Sustainable management of plantations for timber and maximization of productivity requires a thorough understanding of the interactive effects between productivity, environmental conditions, and underlying physiological processes. Identification of limits to productivity can reveal opportunities for its increase. Loblolly pine productivity, e.g., is largely limited by both water and nutrient availability, but their respective effects act through two different response mechanisms (Allen et al. 2005). Nutrient availability largely limits total leaf area that can be attained, while water availability influences the growth efficiency of that leaf area. Although our literature search found fewer publications looking at these underlying mechanisms (compared to commodity-oriented responses), it is important to recognize that controlled silvicultural studies are not the only source of information about these mechanisms. A more complete picture of information available for understanding these mechanisms would require a thorough search for ecophysiological studies that often involve manipulation, but are not established as silvicultural treatments (e.g., van den Driessche 1991 and Ritchie and Keeley 1994).

Cross-Classification by Silvicultural Treatment and Measured Response

A wide array of response categories was measured for each class of silvicultural treatments (Table 6); however, some important gaps also became evident. In particular, the economic aspects of nursery treatments, genetic tree improvement practices, and tree and stand protection efforts were not well covered in the literature. Only 1, 6, and 4%, respectively, of the publications covering these classes included an economic response variable. Wood quality variables also were rarely found in research publications on nursery operations, tree and stand protection, and release treatments. However, this gap does not appear to be as critical since the treatment classes that are considered to be most influential in determining wood quality, namely, initial density, thinning, fertilization, and genetic tree improvement (Gartner 2005), were all more likely to have included wood quality responses.

Some treatment × response links did appear to be driven by the desire to understand response mechanisms. Almost one-third (32%) of the publications documenting fertilization research examined soil properties as one of the response variables, most likely because this silvicultural treatment has a direct impact on soil quality (Fox 2000). Soil responses also were monitored in 26% of the site preparation studies, not surprising given that modification of the soil environment and soil nutrient status through site preparation has yielded mixed results with respect to enhancing or reducing seedling growth (Minore and Weatherly 1990, Piatek et al. 2003, Roberts et al. 2005). Thinning, planting operations, and release treatments have a more indirect impact on soil quality and processes, primarily

Table 6. Number of records for each class of silvicultural treatment in the coastal Douglas-fir from 1984 to 2004, cross-classified by response category.

	Genetic tree imprvmnt	Nursery oper.	Site prep.	Planting oper.	Release trmts.	Fert.	Thinning	Pruning	Tree/stand protection	Total
Growth and yield	55	100	32	69	63	103	89	11	46	390
Economics	6	1	5	14	12	16	24	10	6	63
Wood quality	18	2	1	9	1	9	17	11	2	48
Tree and stand health	23	84	21	41	40	40	47	4	119	280
Soil properties	0	7	12	9	11	46	14	0	5	81
Tree morph. and phys.	16	62	8	17	22	47	30	5	31	177
Photosynthesis	1	5	0	1	3	3	1	0	2	13
Carbon allocation	4	17	0	2	1	12	12	2	6	36
Tree phenology	25	21	0	5	0	0	0	0	11	52
Mycorrhizal structures	0	19	3	6	1	2	0	0	4	29
Total	96	141	46	97	86	146	136	24	147	671

The same record can contribute to more than one cell in the table; therefore, row and column totals exceed the actual number of publications.
Imprvmnt., improvement; fert., fertilization; morph., morphology; oper., operations; phys., physiology; prep., preparation; trmts., treatments.

through changes in soil organic matter accumulation and nutrient cycling induced by greater tree growth (Fox 2000). The number of publications describing response of soil properties to treatments in these classes ranged between 9 and 12%.

Attempts to correlate forest and crop productivity with physical soil properties have not been met with resounding success (Fox 2000, Vance 2000). Predicting the influence of soil characteristics on productivity requires an understanding of the complex interactions between the soil, soil biota, and plants. Directing future silvicultural research toward the aspects of soil dynamics that are deemed influential in controlling productivity, but are underresearched, therefore, is key to being able to better predict how silvicultural regimes are likely to influence the soil environment and, hence, tree and stand growth.

One notable gap was evident in the small number of fertilization and release studies that examined mycorrhizal responses (Table 6). Outside of nursery experiments, only a single publication in the PFI database documented the effects of fertilization on mycorrhizae formation (Colinas et al. 1994), and only a single publication investigated the effects of herbicide application on mycorrhizae formation (Busse et al. 2004). Given the potential effects of herbicide and fertilizer applications on soil fungi, bacteria, and other biota, and the possible consequences for forest productivity, this topic could be an important area for further investigation.

Because morphological, physiological, and environmental mechanisms drive responses to silvicultural manipulations, understanding how these mechanisms actually work in driving growth response assumes greater importance where the growth response to most treatment combinations can not be field tested over reasonable lengths of time, as in plantation silviculture. Representing these mechanisms in growth predictions and formal simulation models should improve the accuracy of interpolations and extrapolations to untested treatment regimes. Predictive models with key response mechanisms represented will also improve the capability to test how robust the new crop is likely to be under future climate scenarios and under changes in other environmental conditions.

Conclusions

The number of research publications on intensive silviculture of coastal Douglas-fir has been clearly declined over the last 20 years. Although many studies investigated the interactive effects of multiple silvicultural treatments, the combinations tested were largely restricted to treatments typically applied at the same stage of stand development. A variety of responses have been represented in the silvicultural studies published from 1984 to 2003. However, most studies that monitored several responses concurrently involved different aspects of the quantity and quality of stemwood, and less than one-half of the studies included environmental, morphological, or physiological processes that reveal mechanisms behind stem growth responses to silvicultural treatments.

In those studies that did examine response mechanisms, the selection of silvicultural treatments apparently was based on their expected potential to influence the processes and response mechanisms of interest. A comprehensive understanding of treatment interactions, however, demands a more strategic choice of treatment regimes and processes based on a working hypothesis derived from the current literature of how individual treatments affect key processes and, ultimately, tree and stand yield. Although the silvicultural treatments should be balanced against operational feasibility, some treatments in this strategy will inevitably serve the purpose of defining the extremes and limits on productivity and thereby boost confidence in predicted responses to untested regimes.

The CAB literature search provided a preliminary assessment of research gaps in plantation silviculture of Douglas-fir over the last 20 years. The most problematic gaps involve yield responses to widely varying silvicultural regimes, largely because the interactive effects of treatments applied at establishment and at midrotation are unknown. The fact that all possible combinations and schedules of treatments can not be field tested underscores the need to determine the limitations that have resulted in the research gaps identified here and for multidisciplinary teams of scientists to strategically select those treatment regimes and responses that are feasible to combine but have been neglected because of other reasons. Estimates of interactions that are not feasible to make through field trials, could be made with more confidence if the second most significant gap did not exist; i.e., specific mechanisms of response to silvicultural treatments. Ecophysiological studies that impose nonoperational manipulations can help identify the important mechanisms underlying tree and stand responses. The future summary and synthesis of the literature catalogued here will help determine which of those mechanisms have been studied in a silvicultural context for Douglas-fir in the Pacific Northwest and which ones need further investigation.

The PFI database provides an important source of information for foresters wishing to expand or hone their knowledge of past research findings, and thereby improve intensive silviculture of planted forests. The planned future synthesis of literature will include not only the papers identified in the CAB Abstract search, but also the key literature before 1984. Another goal is to gain a better perspective for designing a comprehensive research program for the future that covers intensive plantation silviculture of the Douglas-fir and one that explicitly tests our current working hypotheses about how trees and stands respond to individual silvicultural treatments and entire treatment regimes. The ultimate goal is to ensure a viable forest products industry in the Pacific Northwest and to maintain the current land base available for growing forests.

Endnote

[1] Cooperative Forest Research Forum, 2001; Intensive Forestry Research Summit, 2002; Intensive Plantation Forestry Symposium, 2004. Mention of product name for information only and does not imply endorsement by the Federal Government.

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