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Promoting old-growth characteristics and long-term wood production in Douglas-fir forests

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Abstract

Trade-offs among wood production, wood quality and ecological characteristics in the management of harvested forest stands are explored through model simulation of various silvicultural regimes. Long-term production of merchantable wood, production of various types of high-quality wood, and the level of certain quantitative ecological indicators are projected for coniferous forests of Pacific Northwestern USA. The set of ecological indicators used is based on the species composition and physical structure of old, unlogged forest stands. Simulations are performed with an ecological model of forest stand dynamics that tracks the fate of live and dead trees. Short rotations (<50 years) produce the least amount of high-quality wood over the multi-century simulation period. They also fail to generate ecological attributes resembling those of old forest stands. Production of high-quality wood is moderate to high under all rotations of 80 years or more; however, most ecological indicators require longer rotations unless alternatives to clearcutting are applied. Alternatives examined include retention of 15% cover of live tree canopy at each harvest in combination with artificial thinning between harvests. Thinning from below can expedite the development of large live and dead trees, and canopy height diversity without greatly diminishing wood quantity or quality. Proportional thinning retains understory stems, thereby expediting the recruitment of shade-tolerant trees. A possible drawback to thinning, particularly proportional thinning, is the diminished production of clean-bole wood at rotations of 150 and 260 years. It is concluded that most wood quantity, wood quality and ecological objectives can be met with long rotations (ca. 260 years). Certain objectives can be met with shorter rotations (80–150 years) when treatments of thinning and canopy tree retention are applied.

Keywords: Ecological simulation; Forest dynamics; Late-successional characteristics; Pacific Northwest; Rotation length; Silviculture; Wood quality

1. Introduction

Management planning for harvested forest lands requires information on long-term wood yields and ecological consequences of various silvicultural regimes. Understanding of the trade-offs between wood production values and ecological values in forest management over multiple centuries is limited. As a result, uncertainty exists in specifying regimes that meet both sets of values over the long term. In Douglas-fir forests of the Pacific Northwestern US, studies on effects of silvicultural regimes on wood production have shown that different schedules of harvesting and thinning can affect the quantity and the quality of wood produced (Barbour et al., 1997). Short rotations (<50 years) can yield high rates of

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wood production, but the quality of that wood can be low (Senft et al., 1985; Maguire et al., 1991). Several ecological aspects of stand structure and composition are also influenced by silvicultural regime. For example, it is clear that short-rotation regimes (<50 years) create stands that are structurally distinct from most unlogged stands of the region. Short-rotation stands typically lack the large tree boles, vertical heterogeneity of live canopies, and shade-tolerant tree species often found in old, unlogged forests (Franklin et al., 1981). Alternative regimes may provide high wood production over the long term, while enhancing structural and compositional diversity of stands (McComb et al., 1993; Hansen et al., 1995; Acker et al., 1998). Whether such regimes can meet objectives of high wood production, high wood quality, and high ecological quality is addressed here.

This study uses long-term simulations to explore the consequences of several silvicultural regimes for wood production, wood quality and ecological attributes of forest stands. The regimes differ by length of time between harvests (rotation length), timing and type of thinning treatments, and the cover of canopy trees retained at harvest. Comparison of wood yields and quantitative ecological indicators over multiple centuries is accomplished with projections from an ecological model of forest dynamics that tracks live and dead trees.

Key issues include how various regimes affect: (1) the quantity and quality of harvested wood, and (2) the development of late-successional ecological attributes of forest stands. Ultimately, we attempt to identify regimes that produce wood of high quality as well as late-successional stand attributes. We also characterize trade-offs among wood quantity, wood quality and ecological attributes.

2. The model

The long-term effects of silvicultural regimes on wood yields and ecological attributes of stands were explored with an ecological simulator of forest stand dynamics (ZELIG; Urban et al., 1991). ZELIG.PNW (version 3.0; Garman, 1999) is an individual-based simulator of forest dynamics adapted to tall, coniferous forests of western Oregon. It simulates the establishment, growth, and mortality of individual trees on a lattice of interacting plots representing a forest stand or landscape (Urban et al., 1991; Garman et al., 1992; Urban, 1993; Hansen et al., 1995). Each plot is 0.04 ha in area, approximating the zone of influence of a dominant canopy tree.

The simulation time-step is 1 year and the simulation length may be a few years to thousands of years. During a simulation, the species, bole diameter (dbh), and height of each live tree are tracked. Tree height, leaf area and biomass are calculated annually using allometric relationships with bole diameter (dbh). These three measures serve to characterize the competitive environment of plots.

Competitive interactions among trees in the same plot or in neighboring plots can decrease growth and survival of individual trees. Maximum potential tree establishment and growth are calculated annually for each species and individual tree, respectively. Levels of establishment and growth on a plot are subsequently reduced when light, soil moisture, soil fertility or temperature conditions are suboptimal. Low-level mortality is simulated as an annual probability based on species' longevity. Resource-limited trees are subject to an additional, elevated probability of mortality.

Fates of dead tree boles are tracked to provide information on stand structure and the quantity of woody detritus. Simulation of the dynamics of coarse woody detritus is based on the estimates and algorithms of Graham (1982). Boles of recent dead trees become snags or logs which advance through a series of decay classes until decomposition is complete.

The model has been tested for its ability to simulate reasonable forest stand attributes and wood production in western Oregon. Garman et al. (1992) compared simulated forest structure to data from stands up to 500 years since the last major disturbance. They found reasonable agreement between simulated and actual tree density, tree basal area, snag density, and log density for stands 100–500 years old. Goslin (2000) compared ZELIG.PNW projections over the first century of stand development to those of the growth and yield model ORGANON (Hann et al., 1997). Douglas-fir basal area levels and trends were similar between models. Goslin also found good agreement between simulated and actual basal area levels of Douglas-fir over the first 500 years of stand development.

3. The simulations

A first step was to assess the effects of rotation length (or time interval between clearcut harvests) on: (1) the quantity of merchantable wood harvested, (2) the quantity of merchantable wood of high quality, and (3) the physical structure and species composition of stands. Merchantable wood was defined as bole wood with a dbh not less than 18 cm, a stump height of 45 cm, and a top diameter of 10 cm. Wood quality measures included the amount of mature bole wood (wood produced after 20 years of growth from pith; DiLucca, 1989; Maguire et al., 1991), the amount of clean-bole wood (below the live crown), and the amount of ring-dense wood (mean > 8 rings/in. [>3.15/cm]) (Table 1). Selection of these indicators of wood quality was based on wood strength and the capabilities of ZELIG. Mature wood, clean-bole wood, and ring-dense wood are known to be relatively strong (Oliver, 1994). It should be noted that clean-bole wood is an indicator of wood with the potential to develop into unknotted wood. While specific information on branch size and location on the bole cannot be generated with ZELIG, annual changes in dbh and live crown depth are tracked and can be used to generate selected wood quality variables for each tree. Ecological variables included density of large live trees (>1 m dbh), density of large standing dead trees, biomass of fallen logs, vertical heterogeneity of live canopy, and density of shade-tolerant trees (Table 1). Selection of these ecological variables is based on the physical structure and species composition of late-successional or "old-growth" Douglas-fir stands (Franklin et al., 1981). Each of these ecological measures typically increases during long-term stand development following natural, stand-replacing disturbances (Spies and Franklin, 1991).

Simulations were run for 260 years to provide long-term projections of wood yields and stand dynamics on sites of moderately high quality. Initial simulation conditions represented clearcut stands without residual snags, logs or live trees. Planting of Douglas-fir seedlings at a density of 1682 ha^{-1} was simulated at the beginning of each simulation (year 0) and after each timber harvest, excluding thinnings.

Simulation tract area was set at 2.56 ha to account for spatial heterogeneity within stands and to allow efficient simulations (Garman, 1999). Eight replicate tracts were simulated for each harvest regime.

Rotation lengths of 40, 80, 150 and 260 years were selected to represent the full range of intervals between timber harvests commonly used or proposed in recent management plans (e.g. Cissel et al., 1999) for the Oregon Douglas-fir region west of the Cascade Range crest. The 40-year rotation is often used on industrial lands on moderately to highly productive sites. A rotation of about 80 years is also common on moderately to highly productive sites in the region, particularly on state and federal lands. A 150-year rotation is proposed for the maintenance of late-successional stand conditions on certain federal lands within the region (Forest Ecosystem Management Assessment Team, 1993; USDA/USDI/BLM, 1994). In this case, management goals include the development of stands with large live trees, snags and logs. The 260-year rotation approximates the natural return

Table 1
Summary of indicators of wood quantity and quality, and of late-successional stand structure and composition

Attribute	Description and requirements
Wood volume and quality	
Merchantable wood	Bole wood from trees >18 cm dbh; stump height 45 cm; top diameter 10 cm
Mature wood	Merchantable wood excluding a juvenile wood core of the first 20 rings from pith
Clean-bole wood	Merchantable wood excluding crown wood
Ring-dense wood	Merchantable wood with a mean ring-density exceeding 3.15 cm^{-1} (8 $in.^{-1}$)
Ecological attributes of stands	
Mass of log debris	Late-successional level; at least 30 Mg ha^{-1} of items $\geq$10 cm large-end diameter
Number of snags	Late-successional level; at least 10 ha^{-1} of snags >50 cm large-end diameter
Canopy height diversity	Late-successional level; height diversity index (Spies and Cohen, 1992) of at least 8.0
Shade-tolerant tree species	Late-successional level; at least 10 ha^{-1} of shade-tolerant stems >40 cm dbh
Density of large trees	Late-successional level; at least 10 ha^{-1} of live stems >100 cm dbh

interval of stand-replacing disturbances in the study area (Cissel et al., 1999). Although much spatio-temporal variation in such disturbances is likely, and a single typical return interval may not be appropriate, this multiple century rotation allows stands to reach late-successional stages. It also provides habitat and refugia for species requiring long disturbance-free intervals for population viability.

Regimes were simulated with the following thinning treatments: (1) no thinning, (2) thinning from below, and (3) thinning proportional to density in each diameter class up to 60 cm dbh (Table 2). In general, thinning is known to increase diameter growth of residual canopy trees, accelerating wood volume accumulation and the development of large boles (both live and dead) (Forest Ecosystem Management Assessment Team, 1993). Thinning from below involved removing the smallest stems until the specified stem density was reached. Proportional thinning was intended to retain some small stems and all stems >60 cm dbh. It involved removing a proportion of stems from each 5 cm diameter class up to 60 cm dbh so that the specified stem density was attained. Proportional thinning was designed to maintain uneven size structure and uneven age structure within stands. Thinning events occurred on reasonable schedules for each rotation length, and stem densities after planting or thinning events were representative of regimes commonly practiced within the region (James H. Mayo, personal communication).

Regimes were simulated either with or without retention of a portion of canopy trees at each harvest event (Table 2). Simulations with retention kept the largest trees to meet a requirement of at least 15% cover (USDA/USDI/BLM, 1994).

4. Results

Production of merchantable wood, assessed by volume, was affected by rotation length and silvicultural treatments. Under simple clearcutting and planting of Douglas-fir (CP treatments), long-term production was lowest in the 40-year rotation (Fig. 1). Three alternatives to clearcutting (CP treatments) were explored for comparison (Table 2). The alternatives involved retention of 15% canopy cover at timber harvests. The first alternative differed only in

Table 2
Summary of rotation lengths and silvicultural treatments simulated

Code	Rotation length (year)	Harvest type	Post-harvest planting	Thinning type and schedule
CP40	40	Clearcut	Douglas-fir 1682 ha^{-1}	None
CP80	80	Clearcut	Douglas-fir 1682 ha^{-1}	None
CP150	150	Clearcut	Douglas-fir 1682 ha^{-1}	None
CP260	260	Clearcut	Douglas-fir 1682 ha^{-1}	None
CR40	40	Retain 15% canopy cover	Douglas-fir 1682 ha^{-1}	None
CR80	80	Retain 15% canopy cover	Douglas-fir 1682 ha^{-1}	None
CR150	150	Retain 15% canopy cover	Douglas-fir 1682 ha^{-1}	None
CR260	260	Retain 15% canopy cover	Douglas-fir 1682 ha^{-1}	None
TB40	40	Retain 15% canopy cover	Douglas-fir 1682 ha^{-1}	Below; 10-year stand, leave 618 trees/ha
TB80	80	Retain 15% canopy cover	Douglas-fir 1682 ha^{-1}	Same as above (TB40)
TB150	150	Retain 15% canopy cover	Douglas-fir 1682 ha^{-1}	Below; 40-year stand, leave 272 trees/ha; 60-year stand, leave 185 trees/ha; 90-year stand, leave 124 trees/ha
TB260	260	Retain 15% canopy cover	Douglas-fir 1682 ha^{-1}	Same as above (TB150)
TP40	40	Retain 15% canopy cover	Douglas-fir 1682 ha^{-1}	Proportional; 10-year stand, leave 618 trees/ha
TP80	80	Retain 15% canopy cover	Douglas-fir 1682 ha^{-1}	Same as above (TP40)
TP150	150	Retain 15% canopy cover	Douglas-fir 1682 ha^{-1}	Proportional; 40-year stand, leave 272 trees/ha; 60-year stand, leave 185 trees/ha; 90-year stand, leave 124 trees/ha
TP260	260	Retain 15% canopy cover	Douglas-fir 1682 ha^{-1}	Same as above (TP150)

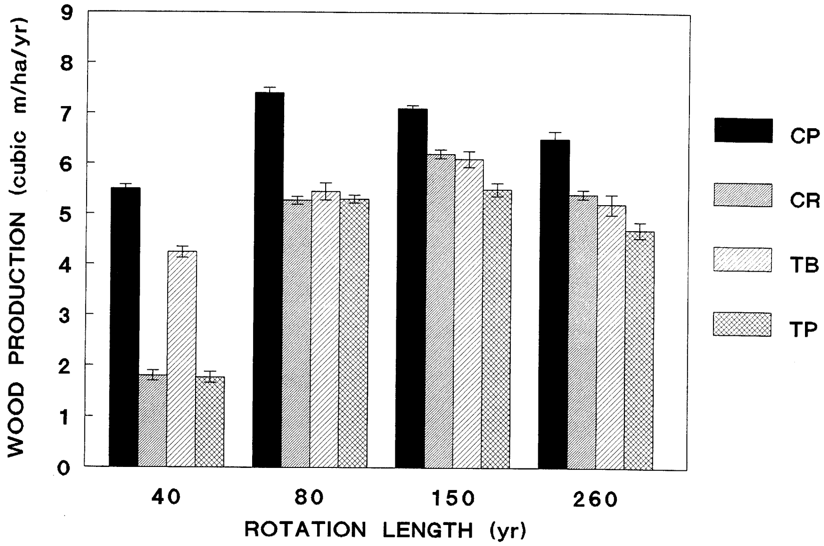

Fig. 1. Mean and standard deviation of long-term production of merchantable wood by rotation length and silvicultural treatment, see Table 2 for treatment codes.

that 15% canopy cover was left at harvests (CR treatments). The second and third alternatives included stand thinning. In thinning from below (TB treatments), smaller stems were removed until a specified density of stems remained. In proportional thinning (TP treatments), only a portion of stems was removed from each size class of small stems. The alternative treatments with canopy tree retention were less productive than simple clearcutting and planting (CP treatments) for all rotation lengths. However, some variation among rotation lengths existed. For example, canopy retention and proportional thinning gave notably low production in the 40-year rotation (Fig. 1).

Production of mature wood was also lowest at the 40-year rotation (Fig. 2). Even under clearcutting followed by planting, the yield from a 40-year rotation was less than half that of longer rotations. The alternative regimes with thinning did not appear to boost mature wood production. To the contrary, under the 40-year rotation proportional thinning greatly diminished yield of mature wood.

Under clearcutting followed by planting, production of bole wood lacking live branches was highest for the 150-year rotation (Fig. 3). However, the alternative treatments with thinning greatly diminished yields of the 40-, 150- and 260-year rotations. Among the alternative treatments with thinning, clean-bole wood yields from the 80-year rotation were the highest.

Production of wood with narrow growth rings was higher at long rotations (Fig. 4). Yields under the 40-year rotation were the lowest by far. Alternatives to clearcutting often gave good yields at rotations longer than 40 years. However, proportional thinning gave diminished yields at the 150- and 260-year rotations.

Several of the selected ecological attributes of forest stands (Table 1) also responded strongly to rotation length and silvicultural treatments. The mean density of large trees (>100 cm dbh) over the course of an entire 260-year simulation was zero for all rotations with simple clearcutting and planting (Fig. 5). Although live trees approached the 100 cm diameter threshold in the longer rotations, none exceeded it. Only the alternative treatments with canopy tree retention produced trees of this size. Thinning from below at a 260-year rotation produced the highest mean densities of large trees.

The mean density of standing dead trees (or snags) tends to increase with rotation length (Fig. 6). All 260-year rotations, regardless of other treatments, gave moderate to high mean densities of snags. The regime with thinning from below appears to enhance snag

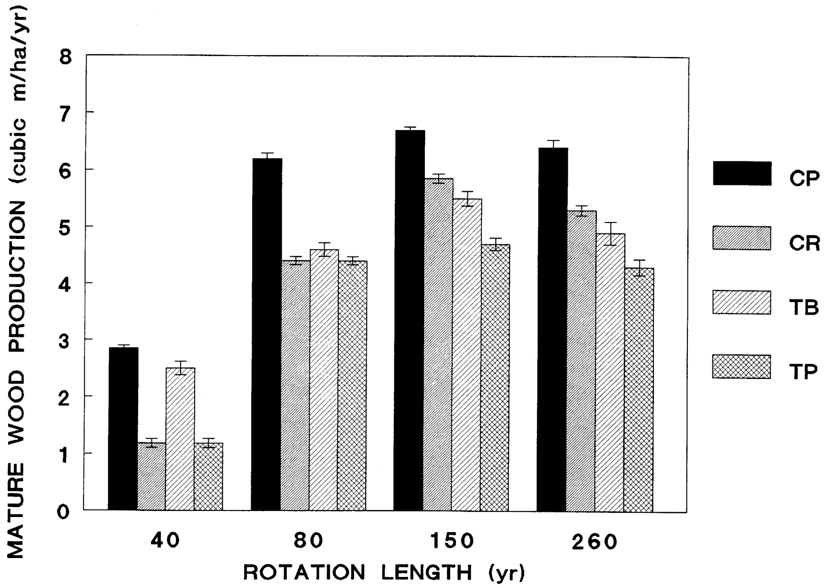

Fig. 2. Mean and standard deviation of long-term production of merchantable mature wood by rotation length and silvicultural treatment, see Table 2 for treatment codes.

densities at rotations of 150 years or less. Mean mass of fallen dead trees (logs) shows a similar pattern except that thinning from below enhances levels only at rotations of 80 years or less (Fig. 7).

Mean height diversity of trees attains maximum values at long rotations (Fig. 8). The regimes with canopy tree retention and thinning enhance height diversity at rotations less than 260 years. Most notably,

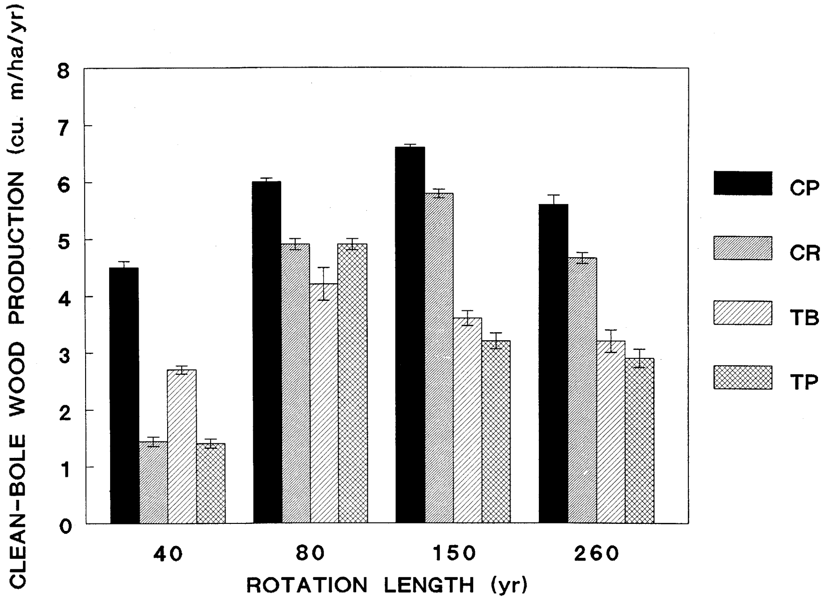

Fig. 3. Mean and standard deviation of long-term production of merchantable clean-bole wood by rotation length and silvicultural treatment, see Table 2 for treatment codes.

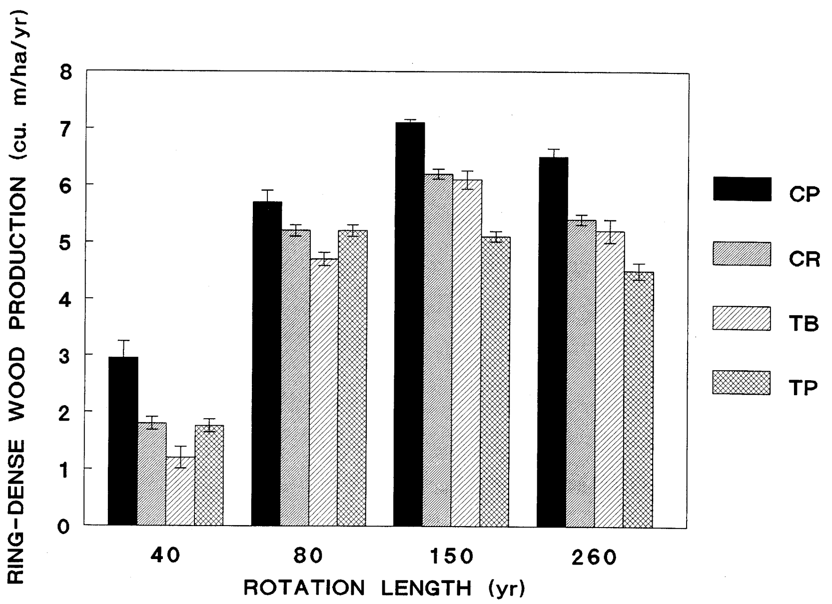

Fig. 4. Mean and standard deviation of long-term production of merchantable ring-dense wood by rotation length and silvicultural treatment, see Table 2 for treatment codes.

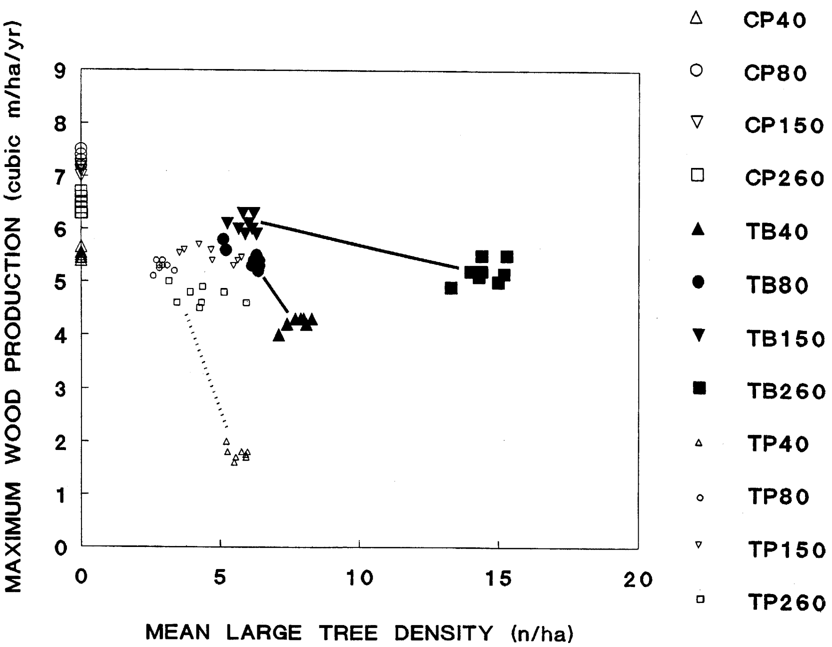

Fig. 5. Long-term wood production versus mean density of large trees for selected rotations and silvicultural treatments. Each point represents a simulation. Lines connect treatments differing only by rotation length, see Table 2 for treatment codes.

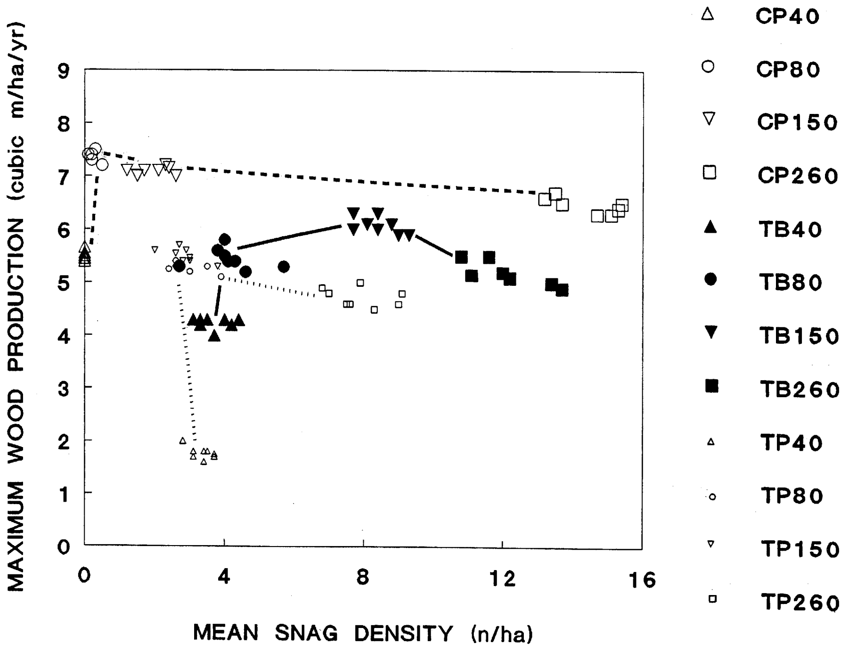

Fig. 6. Long-term wood production versus mean density of snags for selected rotations and silvicultural treatments. Each point represents a simulation. Lines connect treatments differing only by rotation length, see Table 2 for treatment codes.

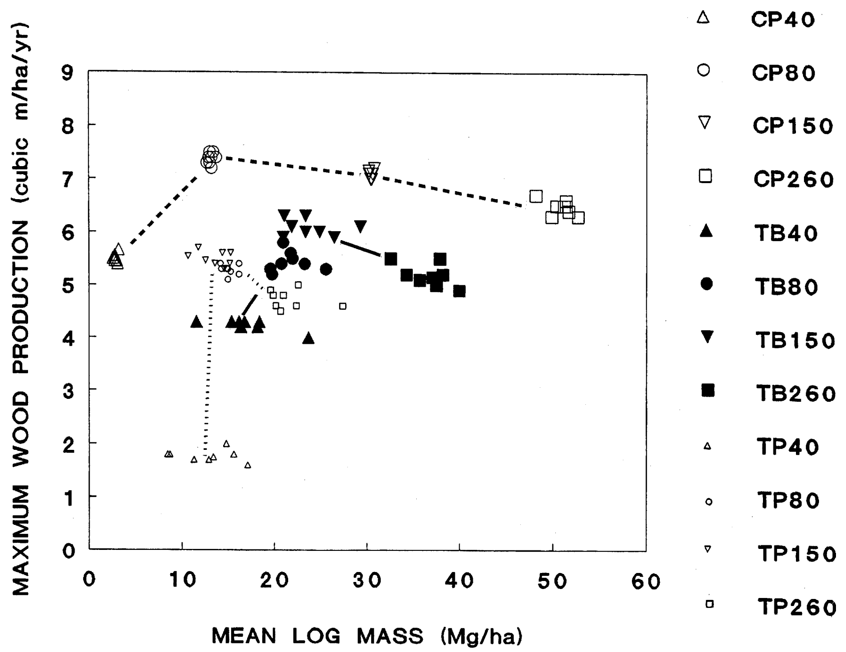

Fig. 7. Long-term wood production versus mean mass of log debris for selected rotations and silvicultural treatments. Each point represents a simulation. Lines connect treatments differing only by rotation length, see Table 2 for treatment codes.

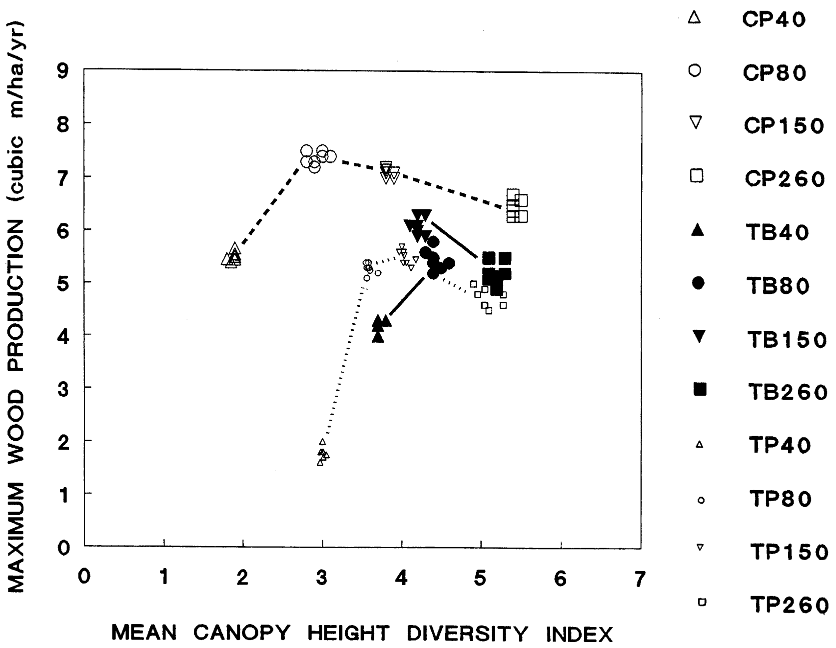

Fig. 8. Long-term wood production versus mean canopy height diversity for selected rotations and silvicultural treatments. Each point represents a simulation. Lines connect treatments differing only by rotation length, see Table 2 for treatment codes.

an 80-year rotation with thinning from below often produces more height diversity than regimes with a 150-year rotation.

The density of shade-tolerant stems is one attribute that is clearly enhanced by proportional thinning (Fig. 9). Mean stem densities of such species are very low in most cases. Only when proportional thinning is combined with rotations of 150 years or more is shade-tolerant stem density elevated greatly.

Relationships between wood production and ecological development are evident when results are compared among treatments. Under simple clearcutting and planting long-term wood production objectives are met at rotations of 80 years or more, but none of the ecological objectives are met at rotations less than 150 years (Table 3). Retention of 15% canopy cover at harvests diminishes wood production somewhat, but promotes the accumulation of logs and increases the density of large trees (Table 4). The combination of canopy tree retention and thinning from below diminishes wood production to a slightly greater degree and sharply decreases the production of clean-bole wood at longer rotations (Table 5). Nonetheless, this combination clearly accelerates the development of the largest number of ecological attributes. When proportional thinning is substituted for thinning from below, wood production diminishes even further (Table 6). Yet, unlike all other treatments simulated, this type of thinning greatly increases the density of shade-tolerant species at rotations of 150 years or more.

5. Discussion

At a time scale of multiple centuries, merchantable wood yields are consistently low among simulations of 40-year rotations. Although such short rotations may provide high short-term yields, they are less productive over the long term. This holds true even though these simulations do not account for potential nutrient losses under short-rotation regimes (Henderson, 1994). Production of high-quality wood is notably low for all simulated 40-year rotations (Tables 3–6). Furthermore, the ecological attributes of stands resulting from 40-year rotations are distinct from older unlogged forests of the Douglas-fir regions of Oregon and Washington (Tables 3–6). The density of

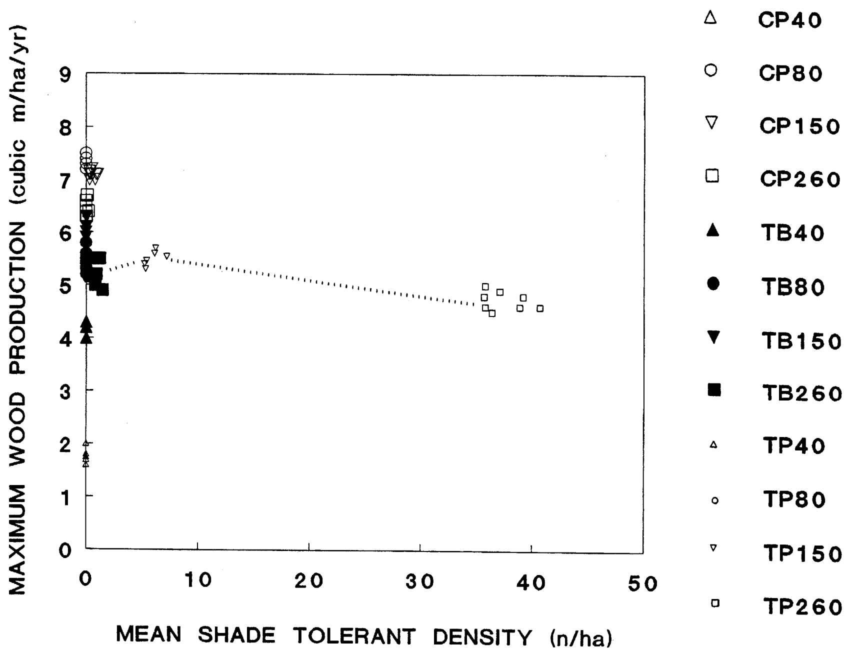

Fig. 9. Long-term wood production versus mean density of shade-tolerant trees for selected rotations and silvicultural treatments. Each point represents a simulation. Lines connect treatments differing only by rotation length, see Table 2 for treatment codes.

snags, the diversity of canopy height, and the density of shade-tolerant tree species are consistently lower in short-rotation stands. However, treatments with thinning and live-tree retention often enhance the density of large live trees and the mass of log debris even in short-rotation stands.

Both wood quality and certain ecological characteristics are enhanced at longer rotations. However,

Table 3
Summary of rotation interval effects on ecological attributes and harvest yields for wood quality categories under clearcutting and planting[a]

Attribute	Harvest rotation			
	40 years	80 years	150 years	260 years
Wood volume and quality				
Merchantable wood quantity	0.74	*1.00*	*0.96*	*0.88*
Mature wood quantity	0.43	*0.93*	*1.00*	*0.96*
Clean-bole wood quantity	0.68	*0.91*	*1.00*	*0.85*
Ring-dense wood quantity	0.42	*0.80*	*1.00*	*0.92*
Ecological attributes of stands				
Mass of log debris	0.18 (0)	0.44 (0)	*1.01* (*0.59*)	*1.70* (*0.60*)
Number of snags	0	0.02 (0)	0.19 (0)	*1.46* (*0.40*)
Canopy height diversity	0.24 (0)	0.38 (0)	0.48 (0)	*0.68* (*0.23*)
Shade-tolerant tree species	0	0	<0.01 (0.02)	<0.01 (0)
Density of large trees	0	0	0	<0.01 (0)

[a] Wood yields are expressed as the ratio of wood volume to maximum simulated production for each category of wood. Ratios for treatments producing 75% or more of the maximum produced for that category by any of the four rotations are given in italics. Ecological attribute ratios of mean values to threshold values are provided. Mean values at least half of the level proposed in old-growth definitions for Douglas-fir forests are given in italics. The proportion of time for each simulation with values at or above the proposed level is provided in parentheses.

Table 4
Summary of rotation interval effects on ecological attributes and harvest yields for wood quality categories under cutting with retention of 15% canopy cover[a]

Attribute	Harvest rotation			
	40 years	80 years	150 years	260 years
Wood volume and quality				
Merchantable wood quantity	0.24	0.71	*0.84*	0.73
Mature wood quantity	0.18	0.65	*0.87*	*0.79*
Clean-bole wood quantity	0.21	*0.75*	*0.88*	0.71
Ring-dense wood quantity	0.25	0.73	*0.87*	*0.76*
Ecological attributes of stands				
Mass of log debris	0.43 (0.11)	*0.51* (*0.06*)	*1.08* (*0.59*)	*1.69* (*0.59*)
Number of snags	0.33 (0)	0.30 (0.01)	0.33 (0.03)	*1.44* (*0.39*)
Canopy height diversity	0.38 (0)	0.45 (0)	*0.60* (*0.09*)	*0.69* (*0.23*)
Shade-tolerant tree species	0	0	0.27 (0)	0.07 (0)
Density of large trees	*0.56* (*0.31*)	0.29 (0.15)	0.12 (0.06)	0.01 (0)

[a] Wood yields are expressed as the ratio of wood volume to maximum simulated production for each category of wood. Ratios for treatments producing 75% or more of the maximum produced for that category by any of the four rotations are given in italics. Ecological attribute ratios of mean values to threshold values are provided. Mean values at least half of the level proposed in old-growth definitions for Douglas-fir forests are given in italics. The proportion of time for each simulation with values at or above the proposed level is provided in parentheses.

the development of ecological characteristics requires longer rotations than does wood quality. For example, simulations with clearcutting followed by planting of Douglas-fir project good production of high-quality wood at rotations of 80 years or more (Table 3). Yet, most of the ecological attributes of stands resulting from 40- to 150-year rotations do not resemble those of old, unlogged forests. Even the stands at the end of a

Table 5
Summary of rotation interval effects on ecological attributes and harvest yields for wood quality categories under clearcutting with thinning from below and retention of 15% canopy cover[a]

Attribute	Harvest rotation			
	40 years	80 years	150 years	260 years
Wood volume and quality				
Merchantable wood quantity	0.57	0.74	*0.82*	0.70
Mature wood quantity	0.37	0.69	*0.82*	0.73
Clean-bole wood quantity	0.41	0.64	0.55	0.48
Ring-dense wood quantity	0.17	0.66	*0.86*	0.73
Ecological attributes of stands				
Mass of log debris	*0.57* (*0.16*)	*0.72* (*0.26*)	*0.80* (*0.39*)	*1.22* (*0.47*)
Number of snags	0.37 (0)	0.42 (0.02)	*0.84* (*0.39*)	*1.21* (*0.61*)
Canopy height diversity	0.46 (0)	*0.55* (*0.01*)	*0.53* (*0*)	*0.65* (*0.09*)
Shade-tolerant tree species	0	0	<0.01 (0)	0.01 (0.02)
Density of large trees	*0.78* (*0.47*)	*0.60* (*0.35*)	*0.59* (*0.32*)	*1.45* (*0.33*)

[a] Wood yields are expressed as the ratio of wood volume to maximum simulated production for each category of wood. Ratios for treatments producing 75% or more of the maximum produced for that category by any of the four rotations are given in italics. Ecological attribute ratios of mean values to threshold values are provided. Mean values at least half of the level proposed in old-growth definitions for Douglas-fir forests are given in italics. The proportion of time for each simulation with values at or above the proposed level is provided in parentheses.

Table 6
Summary of rotation interval effects on ecological attributes and harvest yields for wood quality categories under clearcutting with proportional thinning and retention of 15% canopy cover[a]

Attribute	Harvest rotation			
	40 years	80 years	150 years	260 years
Wood volume and quality				
Merchantable wood quantity	0.24	0.72	0.74	0.64
Mature wood quantity	0.18	0.66	0.70	0.64
Clean-bole wood quantity	0.21	0.74	0.48	0.44
Ring-dense wood quantity	0.25	0.73	0.72	0.63
Ecological attributes of stands				
Mass of log debris	0.43 (0.11)	*0.50* (*0.06*)	0.45 (0.07)	*0.72* (*0.35*)
Number of snags	0	0.02 (0.01)	0.19 (0)	*1.46* (*0.33*)
Canopy height diversity	0.38 (0)	0.45 (0)	*0.51* (*0*)	*0.64* (*0.08*)
Shade-tolerant tree species	0	0	*0.58* (*0.13*)	*3.75* (*0.56*)
Density of large trees	*0.56* (*0.31*)	0.29 (0.15)	0.47 (0.27)	0.43 (0.17)

[a] Wood yields are expressed as the ratio of wood volume to maximum simulated production for each category of wood. Ratios for treatments producing 75% or more of the maximum produced for that category by any of the four rotations are given in italics. Ecological attribute ratios of mean values to threshold values are provided. Mean values at least half of the level proposed in old-growth definitions for Douglas-fir forests are given in italics. The proportion of time for each simulation with values at or above the proposed level is provided in parentheses.

simulated 260-year rotation lack high recruitment of shade-tolerants and very large trees typical of old, unlogged forests.

Alternative treatments with thinning and canopy tree retention produce somewhat less wood, presumably because some canopy trees are left at harvests. On the other hand, certain ecological attributes of older unlogged stands can be attained even at shorter rotations under these regimes. For example, all three alternative treatments allow the development of some large trees even in the 40-year rotations (Tables 4–6). The retention of large trees at harvests is a major factor here since few trees, if any, grow to large size (>100 cm dbh) in 40 years or less.

The two types of thinning treatments simulated give different stand attributes. Thinning from below results in a combination of high densities of large trees, high diversity of canopy height, and high mass of log debris on the forest floor in rotations as short as 80 years (Table 5). In the 260-year rotation, only the density of shade-tolerant species remains low. By contrast, thinning of smaller stems in proportion to their density in diameter classes increases the recruitment of shade-tolerant trees (Table 6) because shade-tolerant trees persist and grow after proportional thinning. None of the other simulated treatments promote high recruitment of shade-tolerant trees. The combination of ecological attributes of 260-year rotation stands with proportional thinning closely resembled that of well-developed unlogged stands. Drawbacks to long rotations under this treatment are the low amount of clean-bole wood produced, the diminished density of snags and very large canopy trees, and the diminished diversity of canopy height. Thinning of this type apparently allows deeper tree crowns, reducing the production of clean-bole wood. Also, the removal of some residual canopy trees appears to have a negative impact on the recruitment of snags and very large canopy trees. Perhaps methods of proportional thinning that do not remove retained canopy trees would meet more of the ecological objectives.

The simulation results, covering rotation lengths from 40 to 260 years, support earlier inferences and findings (e.g. Weigand et al., 1994; Hansen et al., 1995; Curtis and Carey, 1996). Wood quality and ecological quality tend to be inferior at very short rotations (e.g. 40 years). A sharp increase in wood quality tends to occur when shifting from a 40-year rotation to rotations of at least 80 years, as the proportion of juvenile wood, the proportion of crown wood, and the widths of annual rings are notably high among 40-year stands. The development of stands with certain ecological characteristics may require much longer rotations (e.g. at least 260 years) unless thinning and canopy tree retention are implemented (Tables 3–6). With thinning and retention treatments several specified aspects of forest structure and composition can develop even under 80- and 150-year rotations. For example, development of log mass, canopy height diversity, and large tree density is accelerated by thinning from below, and ingrowth of shade-tolerant tree species is accelerated by proportional thinning. Even so, the 260-year rotation satisfies the largest number of ecological indicators in all cases considered.

In a related study, Garman (1999) used the ZELIG.PNW model to explore the degree to which various silvicultural regimes accelerate development of late-successional attributes (listed in Table 1). Treatments were applied to a 40-year old Douglas-fir stand. In general, thinning early in stand development (stand age 40–80 years) combined with canopy tree retention led to development of late-successional attributes in stands as young as 120–180 years. Of the hundreds of thinning regimes simulated in that study, many produced late-successional characteristics in 150-year old stands, suggesting that a single ideal treatment does not exist. Depending on the ecological attributes and the yield of merchantable wood desired, certain treatments can be recommended. For example, heavy thinning beginning at stand ages of 40–60 years provides rapid development of large boles, height diversity, and tree species diversity often at the expense of high wood volume yields. Delaying the first thinning can increase wood volume yields. It also allows further understory development, thereby enhancing height diversity and ingrowth of shade-tolerant species. So, the level of understory development at thinning determines the residual understory and, in turn has a strong affect on certain ecological characteristics.

How well the ecological indicators used in this study represent ecological quality deserves consideration. The set of indicators (see Table 1) represents old, unlogged forests (Franklin and Spies, 1991). Promoting the development of stands with structure and composition resembling older forests of the region is a major objective of the Northwest Forest Plan (USDA/USDI/BLM, 1994; Tuchmann et al., 1996). Some structural characteristics of old forest stands have clear and distinctive ecological benefits. For example, woody debris (snags and logs) provides habitat for a wide variety of organisms, sequesters carbon and maintains soil productivity (Franklin et al., 1981; Harmon et al., 1986; McComb et al., 1993). Heterogeneous canopy (or foliage) height structure promotes diversity of epiphytes and animals (Franklin et al., 1981; McComb et al., 1993; Carey and Johnson, 1995; Hansen et al., 1995). Large live trees store carbon and enhance vertical structure (Franklin et al., 1981; McComb et al., 1993; Curtis and Carey, 1996).

It must be cautioned that stands treated for rapid development of stand structure and composition similar to that of old stands do not necessarily have ecosystem processes similar to those of old stands. For example, long rotations may be required for the accumulation of organic matter, essential nutrients and key species (Henderson, 1994). Long rotations may also promote local and regional biodiversity by providing refugia for species that are sensitive to disturbance and recover slowly (Halpern and Spies, 1995). Simply creating stands that look like old stands may miss some essential aspects of forest community and ecosystem dynamics. For this reason, when there is a choice between long and short rotations, long rotations are recommended. Another option is to retain some canopy trees at harvests. This appears to enhance persistence of late-successional species (e.g. certain lichens; Peck and McCune, 1997), but further study of the quantity and spatial pattern of retained canopy trees required to sustain ecosystem processes and biodiversity is needed (e.g. Halpern et al., 1999).

As a final point, the strengths and weaknesses of our modeling approach are considered. A weakness of ecological simulators is the potential for inferior accuracy in projecting wood production levels for a given site. Certainly, forest growth models calibrated to specific sites are likely to be more accurate than a generalized model at those sites. So the actual wood production levels presented here should be interpreted as general values for the study region. The same holds for the ecological measures presented. Concerning wood quality, the inability to explicitly track branch size and location, which affect knot patterns, is a weakness. Nonetheless, the model is well-suited to the analysis of long-term trade-offs among wood production, wood quality and ecological quality.

Strengths of the ecological forest model in this case are the long time-frames simulated, and the ability to track trends in wood production and in several ecological variables.

6. Conclusions

A contribution of this study is the long-term projection of quantitative values for a variety of indicators of wood production, wood quality and ecological quality. Wood quality and certain ecological characteristics tend to increase at rotation lengths greater than 40 years. Under regimes of clearcutting followed by planting of Douglas-fir, good yields of high-quality wood can be obtained with rotations as short as 80 years. However, most ecological objectives considered here require longer rotations. Without alternative silvicultural regimes, only multiple century rotations satisfy the combined objectives of wood quality and ecological quality. Alternative silvicultural regimes can accelerate the development of stand composition and structure typical of old, unlogged forests. Silvicultural thinning of young stands promotes growth, allowing certain ecological characteristics to develop at rotations less than 260 years. Thinning from below produces large boles and can enhance canopy height diversity. Thinning proportional to density in smaller diameter classes leaves some small stems and facilitates recruitment of shade-tolerant species. However, thinning, especially proportional thinning, can remove canopy trees and increase crown depth, thereby diminishing some aspects of ecological quality and wood quality. Retention of 15% canopy tree cover at harvests reduces wood production, but over the long term it allows the development of large trees even under short rotations. In turn, retention enhances canopy height diversity and the accumulation of woody debris.

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