Density Management in Pacific Northwest Forests:
Economic Strategies and Biological Implications

The Engine Driving the System:
Biological Responses to Stand Density Management

Doug Maguire
Center for Intensive Planted-forest Silviculture
College of Forestry, Oregon State University
## Biological responses to stand density management

<table>
<thead>
<tr>
<th>Tree growth</th>
<th>Carrying capacity</th>
<th>Microclimate</th>
<th>Physiology</th>
<th>Summary</th>
</tr>
</thead>
</table>

- Individual tree growth and allometry
- Carrying capacity
  - Site resource availability
  - Maximum size-density limit
  - Stand growth
- Microclimatic effects
- Key physiological mechanisms
- Summary
Individual tree growth and allometry

Density management

Close (initial) spacing
Light thinning

Wide (initial) spacing
Heavy thinning
Individual tree growth and allometry

Spatial arrangement as part of density management
Individual tree response to spacing/thinning

- Smaller stem diameter
- Similar top height
- Larger H/D
- Smaller crown
- Younger and smaller branches
- More cylindric stem form

- Larger stem diameter
- Similar top height
- Smaller H/D
- Larger crown
- Older and larger branches
- More conic stem form
Trends in SDI over time on Hoskins LOGS plots: Eight different thinning regimes + unthinned control

Marshall and Curtis 2002
Trends in DIAMETER GROWTH of largest trees on Hoskins LOGS plots

Marshall and Curtis 2002

60% larger than control D40 at year 55
Crowns: A key driver of growth and other responses
General increase in crown length over time

- Total height
- Crown base close spacing
- Crown base wide spacing

Diagram showing the growth of trees with different spacing conditions over age (yrs) and height.
Trends in crown ratio over time on Hoskins LOGS plots

Decreasing ratio of photosynthetic capacity to maintenance load; e.g., ratio of foliage mass to live cells

Marshall and Curtis 2002
<table>
<thead>
<tr>
<th>Tree growth</th>
<th>Carrying capacity</th>
<th>Microclimate</th>
<th>Physiology</th>
<th>Summary</th>
</tr>
</thead>
</table>

**Individual tree growth and allometry**

*Ok, but what’s NEW?*
### Early (4-6-yr) spacing effect in Douglas-fir plantations

<table>
<thead>
<tr>
<th>Tree growth</th>
<th>Carrying capacity</th>
<th>Microclimate</th>
<th>Physiology</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing height and diameter growth with decreasing spacing</td>
<td></td>
<td></td>
<td></td>
<td>(Scott et al. 1998)</td>
</tr>
</tbody>
</table>

120 tpa (19-ft)  
1200 tpa (6-ft)

(Scott et al. 1998)
Later spacing effect (23-25-yr) in Douglas-fir plantations

- Little effect of spacing on top height
- Greater dbh with wider initial spacing
- Maximum stand volume at closer spacing
- Little mortality at 10-ft (3-m) spacing up to 25 yrs

(Harrington et al., in press)
Individual tree growth and allometry

But what about other individual tree responses?
**Biological responses to stand density management**

- Shawnigan Lake, BC
- 24-yr-old Douglas-fir stand
- Site index 70 ft at 50 yrs
- Thinned from 100 ft²/ac to 36 ft²/ac
- Response after 7 yrs
  - Crown lengthens
  - Crown accrues foliage at base (longer period of branch development)

*Brix 1981*
Large difference in foliage distribution (at crown closure and at a given LAI) (tree and stand-level)

Garber & Maguire 2002
Ramifications of increasing crown size

- A: Close initial spacing
- B: Average initial spacing
- C: Wide initial spacing
Other stem/log attributes

Gradients in micro-anatomical properties associated with cambial age and/or crown position

Crown wood?

Josza and Middleton 1994
Crown wood/juvenile wood core

Close spacing

Wide spacing

crown base

Crown wood core

Mature wood

crown base
Heartwood/sapwood zones

Close spacing

Wide spacing

crown base

Heart wood core

Sapwood shell

crown base
SMC Initial spacing trial (Type 3)

914 Lewisburg Saddle

Simulation and current analytical tools; e.g., effect of density regime on knot size
SMC Initial spacing trial (Type 3)

914 Lewisburg Saddle

- Planted in winter 1989
- 1-1 Douglas-fir
- Six spacings

<table>
<thead>
<tr>
<th>Spacing (ft)</th>
<th>TPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1210</td>
</tr>
<tr>
<td>8</td>
<td>680</td>
</tr>
<tr>
<td>10</td>
<td>435</td>
</tr>
<tr>
<td>12</td>
<td>300</td>
</tr>
<tr>
<td>15</td>
<td>200</td>
</tr>
<tr>
<td>21</td>
<td>100</td>
</tr>
</tbody>
</table>

- Chemical release in 1989 and 1990
SMC Initial spacing trial (Type 3)

914 Lewisburg Saddle

Age 19 years

6-ft spacing

10-ft spacing

21-ft spacing
Simulates tree and stand development, including crown size.

Crown dynamics allow estimation of branch size and crown wood core.
Initial conditions from measurements at age 14.
Stands simulated 25 years to age 49.
Branch diameter profiles at age 49 (50 percentile)
Cumulative number of trees with smaller average branch diameter in 1st 16-ft log
Crown wood core under three initial spacings (tree representing 90 percentile)
<table>
<thead>
<tr>
<th>Tree growth</th>
<th>Carrying capacity</th>
<th>Microclimate</th>
<th>Physiology</th>
<th>Summary</th>
</tr>
</thead>
</table>

**Stand-level responses & carrying capacity**

- Site resource availability
- Maximum size-density limit
- Growth-growing stock relationships
Determinants of carrying capacity

Solar radiation and heat

species/genotype

Maximum amount of living mass

Soil water and nutrients
Stand development
Crown closure
Size/crown differentiation
Suppression mortality
Maximumum leaf area ?
Maximum resiping biomass ?
Surrogates?
Stand density index

Size-density limit (maximum SDI)

For Douglas-fir, this line has been inferred to be SDI=520-590
Carrying capacity is difficult to predict

Maximum SDI for individual permanent plots:

**Douglas-fir**
- 270-660

**Western hemlock**
- 470-780

*Hann et al. 2004*
A stand starts off with a given number of trees per unit area.

When it approaches its size density limit, suppressed trees begin to die, and surviving trees can grow bigger.
Density

Tree size

Zone of competition
Mortality (relative density=0.55)

Minimum recommended density to maintain site occupancy (relative density=0.35)

Approximate crown closure (relative density=0.15)

Maximum SDI (relative density=1.00)
Trends in SDI over time on Hoskins LOGS plots

Marshall and Curtis 2002
<table>
<thead>
<tr>
<th>Species</th>
<th>SDI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ponderosa pine (Eastside)</td>
<td>365</td>
</tr>
<tr>
<td>Red alder</td>
<td>450</td>
</tr>
<tr>
<td>Grand fir (Eastside)</td>
<td>560</td>
</tr>
<tr>
<td>Douglas-fir</td>
<td>595 (520)</td>
</tr>
<tr>
<td>Western redcedar</td>
<td>722</td>
</tr>
<tr>
<td>Western hemlock</td>
<td>850</td>
</tr>
</tbody>
</table>
Trends in SDI over time on Hoskins LOGS plots

Marshall and Curtis 2002
Let’s take a look at whole-stand behavior

Fundamental drivers

1. A site has a fixed capacity for net primary production (dry weight of all plant material)

2. Initial spacing and thinning determine:
   a. How many stems production accrues on
   b. The length of time that some growing space is at least temporarily unoccupied (resources not used by trees, perhaps other vegetation as well)
Trends in STANDING cubic volume on Hoskins LOGS plots

Light thinning regime

Unthinned control

Marshall and Curtis 2002
STANDING + CUT volume

Marshall and Curtis 2002
Trends in VOLUME PAI over STAND DENSITY on Hoskins LOGS plots

Mid-period Relative Density

Unthinned control

Heavy thinning

Marshall and Curtis 2002
Trends in PERCENT VOLUME GROWTH on Hoskins LOGS plots

Marshall and Curtis 2002
Trends in board-foot volume increment: PAI and MAI

- Periodic annual increment
- Mean annual increment
- Biological rotation age
Trends in MERCHANDABLE CUBIC VOLUME PAI and MAI on Hoskins LOGS plots

Marshall and Curtis 2002
Trends in SCRIBNER VOLUME PAI and MAI on Hoskins LOGS plots

Marshall and Curtis 2002
Effect of thinning type on growth – growing stock relationships

Three treatments:
- Unthinned control
  - RD ~ 70
- Low thinning (from below)
  - RD ~70 → ~44
- Crown thinning (from above)
  - RD ~70 → ~54

Emmingham et al 2007
Relatively low growth with crown thinning (despite greater stand density)

Emmingham et al 2007
Understory response to thinning

Thinning

Understory vegetation is happy to use resources that are not captured by trees!
Understory response to thinning

Low seedling frequency

High seedling frequency

Seedling Frequency
- High (> 0.30)
- Medium (0.10–0.30)
- Low (< 0.10)
- Zero

Bailey and Tappeiner 2008
Understory response to thinning

Pulse of ground vegetation
Interaction of stand density and shrub cover on seedling establishment and survival

Bailey and Tappeiner 2008
Changes imposed by thinning

Canopy reduction as the driver of many/most ecosystem responses
<table>
<thead>
<tr>
<th>Tree growth</th>
<th>Carrying capacity</th>
<th>Microclimate</th>
<th>Physiology</th>
<th>Summary</th>
</tr>
</thead>
</table>

**Resource availability**

**Solar radiation**

- unthinned
- thinned
<table>
<thead>
<tr>
<th>Tree growth</th>
<th>Carrying capacity</th>
<th>Microclimate</th>
<th>Physiology</th>
<th>Summary</th>
</tr>
</thead>
</table>

**Resource availability**

**Solar radiation**

![Diagram showing the effect of unthinned and thinned trees on solar radiation](image)
Resource availability

**PRECIPITATION**

MORE canopy interception

LESS water per tree

LESS canopy interception

MORE water per tree

unthinned

thinned
Resource availability

<table>
<thead>
<tr>
<th>Tree growth</th>
<th>Carrying capacity</th>
<th>Microclimate</th>
<th>Physiology</th>
<th>Summary</th>
</tr>
</thead>
</table>

High stand density

Low stand density

LIMITED soil moisture and LOWER temperature extremes

GREATER soil moisture and temperature

GREATER mineralization rates & nutrient availability
Wind damage

Deeper penetration of wind
More turbulence & sheer stress

Thinning

Tree growth  Carrying capacity  Microclimate  Physiology  Summary
Key physiological mechanisms
### Key physiological mechanisms

<table>
<thead>
<tr>
<th>Tree growth</th>
<th>Carrying capacity</th>
<th>Microclimate</th>
<th><strong>Physiology</strong></th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **MORE evapo-transpiration**
  - High stand density
- **LESS evapo-transpiration**
  - Low stand density
Key physiological mechanisms

Seasonal changes in soil water potential, average for 3 soil depths for years 1972-1981 (Brix and Mitchell 1986)

Thinned plots have greatest water availability
Key physiological mechanisms

Unthinned

Thinned

More light and greater photosynthetic rate in lower crown

Brix 1993
Aboveground biomass increment

from Brix (1983)

Direct + indirect effect
Aboveground biomass increment per unit initial foliage mass

Growth efficiency

from Brix (1983)

Direct effect
+ functional insight

Year

Growth efficiency (kg/kg foliage)

Control
Thin
Fertilize
Thin + Fertilize
Key physiological mechanisms

Contribution of increased foliage efficiency to tree growth response (increase in growth relative to control tree)

100% in years 1 & 2
50% in year 3
0% by year 4
Thinning reduces leaf area index and site occupancy

Fertilization increases rate of leaf area build-up

From Brix (1981)
From Brix (1981)

Longer crowns implies larger number of branch whorls, BUT ALSO . . .
A larger number of secondary shoots on primary branch after thinning

From Brix (1981)
## Thinning effects on allocation

<table>
<thead>
<tr>
<th></th>
<th>Tree growth</th>
<th>Carrying capacity</th>
<th>Microclimate</th>
<th>Physiology</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPP</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>NPP</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>NPP / GPP</td>
<td>0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Tree / other vegetation</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Crop tree / other trees</td>
<td>+</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Shoot / root</td>
<td>0</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Stem / crown</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Merchantable / non-merchantable</td>
<td>+</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Stem form</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
Thinning effects on allocation of x-sectional increment on stem

[Graph showing needle dry weight (g) vs. whorl from tree tip for thinned and unthinned trees.]
Principles

- Individual tree growth response to thinning
  - Accelerates initially due to increased resource availability
  - Increases indirectly and over long term from build-up of foliar mass
  - Crown length increases; crown ratio decreases at decelerating rate
  - H/D declines
  - Change in stem form generally leads to greater taper (but impact depends on crown height at time of thinning)
**Principles**

- Stand growth response to thinning
  - Total biomass/volume production declines
  - Merchantable (recovered) volume can exceed unthinned controls
  - Volume growth increases with increasing residual stand density
  - Volume growth percentage declines with age but does not vary much with stand density
  - Understory vegetation responds positively to increase in resource availability (at least temporarily)
  - Variable-density thinning creates gradients in or patches of varying density within a stand, at a wide range of possible spatial scales
Principles

- **Ecosystem responses**
  - Greater throughfall precipitation
  - Lower evapotranspiration
  - Greater solar radiation to forest floor
  - Greater forest floor temperatures in summer
  - Increase mineralization of organic matter
Principles

• Physiological responses
  – Greater net photosynthetic rate at a given depth into crown
  – Greater foliage efficiency (production per unit foliage) for ~4 years after stand density reduction
  – Shifts in allocation of photosynthates within trees and other individual plants (e.g., fruiting in understory plants)
Thanks!