Optimizing the harvest timing in uneven-aged forestry

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Even- vs. Uneven-aged forestry

Rotation vs. Continuous cover forestry

- Even-aged, or Rotation forestry (Faustmann 1849, Samuelson 1976)
  - Artificial regeneration
  - Clearcuts e.g. every 75 years
- Uneven-aged, or Continuous cover forestry
  - Natural regeneration
  - Selection cuttings e.g. every 10-25 years

Background

- Traditionally clearcuts and artificial regeneration (Siiskonen 2007; Lundmark et al. 2013; Gauthier et al. 2009)
- The analyses have focused on even-aged management following Faustmann (1849) and Samuelson (1976)
- Interest towards uneven-aged management has increased (Lämås and Fries 1995; Bergeron and Harvey 1997; O'Hara 2002; Axelsson and Angelstam 2011)
- Heterogeneous stands provide higher non-timber values and resilience against e.g. climate change (Noss 2001; Thompson et al. 2009; IPCC 2014)

Literature review

- Existing economic studies applying general dynamic optimization use fixed harvesting interval (e.g. Haight 1987, Haight & Monserud 1990a; b; Tahvonen 2009; Tahvonen et al. 2010; Tahvonen 2011; Rämö & Tahvonen 2014).
  - Not possible to study the optimal transition towards the optimal steady state!

- AFAWK, Wikström (2000) the only paper in which the harvest interval may vary
  - Additional constraints e.g. on stand volume

- Only few papers study the transition from even to uneven-aged stands (e.g. Tahvonen et al. 2010; Tahvonen 2011)

Optimizing the harvest timing

- Not only what to harvest, but also when
- Allows to study
  - optimal, unconstrained uneven-aged management
  - optimal transitioning from even-aged to uneven-aged

- Without fixed harvesting cost it is optimal to harvest every period (e.g. Rämö & Tahvonen 2014)
  - Results in low yields

  → Include fixed costs

Optimizing the harvest timing

- Mixed-integer nonlinear problem
  - Computationally very demanding
- With the fixed costs we have a timing problem in a discrete-time mixed-integer model
- Solved using bilevel optimization (Colson et al. 2007)
  - Applied e.g. in Stackelberg (1952) leader-follower game theory setting
  - Harvest timing is optimized using random restart hill-climbing algorithm (Russell & Norvig 2009, p. 122–125)
  - Harvest intensities are optimized with Knitro optimization software

Growth model

Bollandsås et al. (2008)

- Empirically estimated, size structured transition matrix growth model for uneven-aged stands
- Norway spruce at H_{100}=24

Diameter increment

$$I_{st} = 14.8398 + 0.0476\delta_s - 11.585\delta_s^{\,2} - 0.3412BAL_{st} - 0.024BA_t$$

Ingrowth $$\phi_t = \frac{-2.99BA_t^{\,-0.018}}{1 + e^{-(53.142 - 0.157BA_t)}}$$

Natural mortality $$\mu_{st} = \left(1 + e^{-\left(-2.492 - 0.02\delta_s + 3.2\delta_s^{\,2} + 0.031BA_t\right)}\right)^{-1}$$

Cost function

Empirically estimated (Nurminen et al. 2006, Surakka & Siren 2010)

$$C_t = \overbrace{\sum_{s=1}^{n} h_{st}\left[0.412 + 0.758 v_s - 0.180 v_s^{\,2}\right]}^{\textit{Moving \& cutting time}} 1.15\, C_{cut}$$
$$+ \underbrace{\left[17.838 g_t + 2.272 \sum_{s=1}^{n} h_{st} v_s + 0.535 \left(\sum_{s=1}^{n} h_{st} v_s\right)^{0.7}\right]}_{\textit{Hauling time}} C_{haul} + g_t C_{fixed}$$

$v_s = v_{s,sawn} + v_{s,pulp}$

Hauling costs, C_{haul}, are set to 60 € per hour

Moving and cutting costs, C_{cut}, to 126 € per hour

Fixed costs 100-500 €

Optimization problem

$$\max_{\{g_t \in \mathbf{g},\ h_{st} \in \mathbf{h}\}} \pi = \sum_{t=0}^{\infty} \left(\sum_{s=1}^{n} \sum_{j=1}^{k} h_{st} p_j v_{sj} \ - C_t \left(\mathbf{h}_t , \mathbf{v}_s \right) \right) b^{5t}$$

subject to

$$x_{1,t+1} = \phi(\mathbf{x}_t) + \gamma_1(\mathbf{x}_t) x_{1t} - h_{1t}$$

$$x_{s+1,t+1} = \beta_s(\mathbf{x}_t) x_{st} + \gamma_{s+1}(\mathbf{x}_t) x_{s+1,t} - h_{s+1,t}$$

$$x_{n,t+1} = \beta_{n-1}(\mathbf{x}_t) x_{n-1,t} + \left(1 - \mu_s(\mathbf{x}_t)\right) x_{nt} - h_{nt}$$

$$s = 1,2,\ldots,\mathrm{n}-2,\ t = 0,1,2\ldots$$

$$g_t \in \square : [0,1]$$

$$h_{st} = g_t h_{st}\ \forall t \in \square : [0,1,2,\ldots\infty)$$

$$h_{st} \geq 0, x_{st} \geq 0,\ s = 1,2,\ldots,n, t = 0,1,2\ldots$$

Results

Effect of fixed harvesting cost

Younger even aged stand	Fixed cost, €		
Harvest	**100**	**300**	**500**
1	5	10	10
2	15	25	25
3	25	40	55
4	35	55	80
5	45	70	105
Steady state interval	10	15	25

Old even aged stand	Fixed cost, €		
Harvest	**100**	**300**	**500**
1	0	0	0
2	45	45	55
3	55	60	80
4	65	75	105
5	75	90	130
Steady state interval	10	15	25

Uneven-aged stand	Fixed cost, €		
Harvest	**100**	**300**	**500**
1	0	0	0
2	10	15	25
3	20	30	50
4	30	55	75
5	40	70	100
Steady state interval	10	15	25

Optimal times of transition harvests and steady state interval from different initial states with fixed harvesting costs of 100€, 300€ and 500€ with 3% interest rate.

Transition depends on initial state, while steady states are the same

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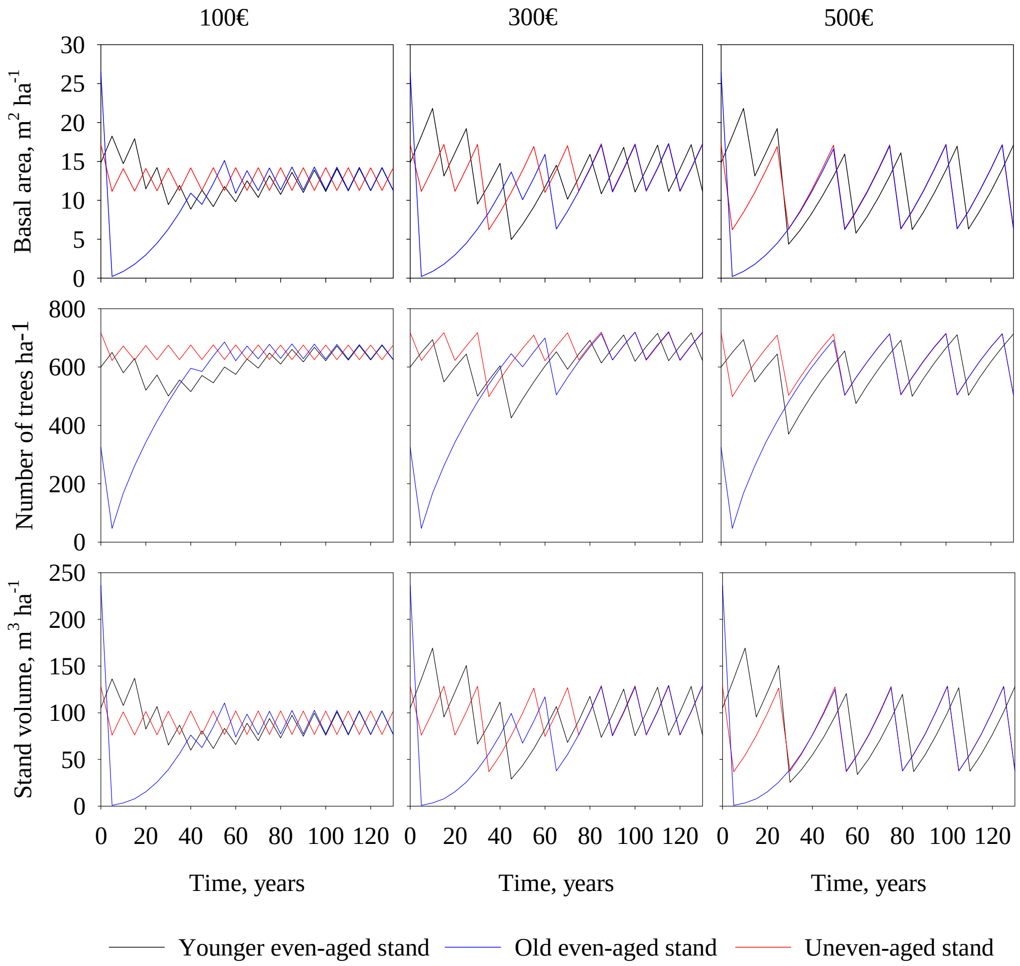

Stand basal area, number of trees and stand volume development from different initial stands with 3% interest rate, and fixed harvesting costs of 100€, 300€ and 500€.

Effect of fixed harvesting cost

Optimal steady states

Fixed harvesting cost, EUR	Average annual yield, m^3 ha^{-1}	Profit per harvest, EUR ha^{-1}	No. of harvested trees per harvest, ha^{-1}	No. of trees after harvests ha^{-1}	Basal area before/after harvests, m^3 ha^{-1}	Average annual natural mortality, trees ha^{-1}	Average annual ingrowth, trees ha^{-1}	Diameter of harvested trees, cm
100	5.3	2513	95	626	20.3/11.3	2.3	11.7	25-34,9
300	5.5	3795	136	623	26.6/11.2	2.4	11.4	25-39.9
500	4.8	5304	250	618	31.2/6.3	2.2	12.2	20-44.9

The higher the fixed cost, the longer the interval and the heavier the harvests

Effect of interest rate

Optimal steady states, 1-5% interest rate, 300€ fixed cost

Interest rate	Average annual yield, m^3 ha^{-1}	Profit per harvest, EUR ha^{-1}	No. of harvested trees per harvest, ha^{-1}	No. of trees after harvests ha^{-1}	Basal area before/after harvests, m^3 ha^{-1}	Average annual natural mortality, trees ha^{-1}	Average annual ingrowth, trees ha^{-1}	Diameter of harvested trees, cm
1 %	6.1	4438	109	717	33.7/16.9	3.0	10.3	30-44.9
2 %	5.6	5352	172	619	33.0/11.0	2.5	11.2	25-44.9
3 %	5.5	3795	136	623	26.6/11.2	2.4	11.4	25-39.9
4 %	4.6	4059	209	507	25.0/6.4	2.0	12.5	20-39.9
5 %	4.3	2727	163	511	19.2/6.5	1.9	12.8	20-34.9

The higher the interest rate, the lower the stand density

Less dense stand results in higher growth rate due to density dependency

Effect of interest rate

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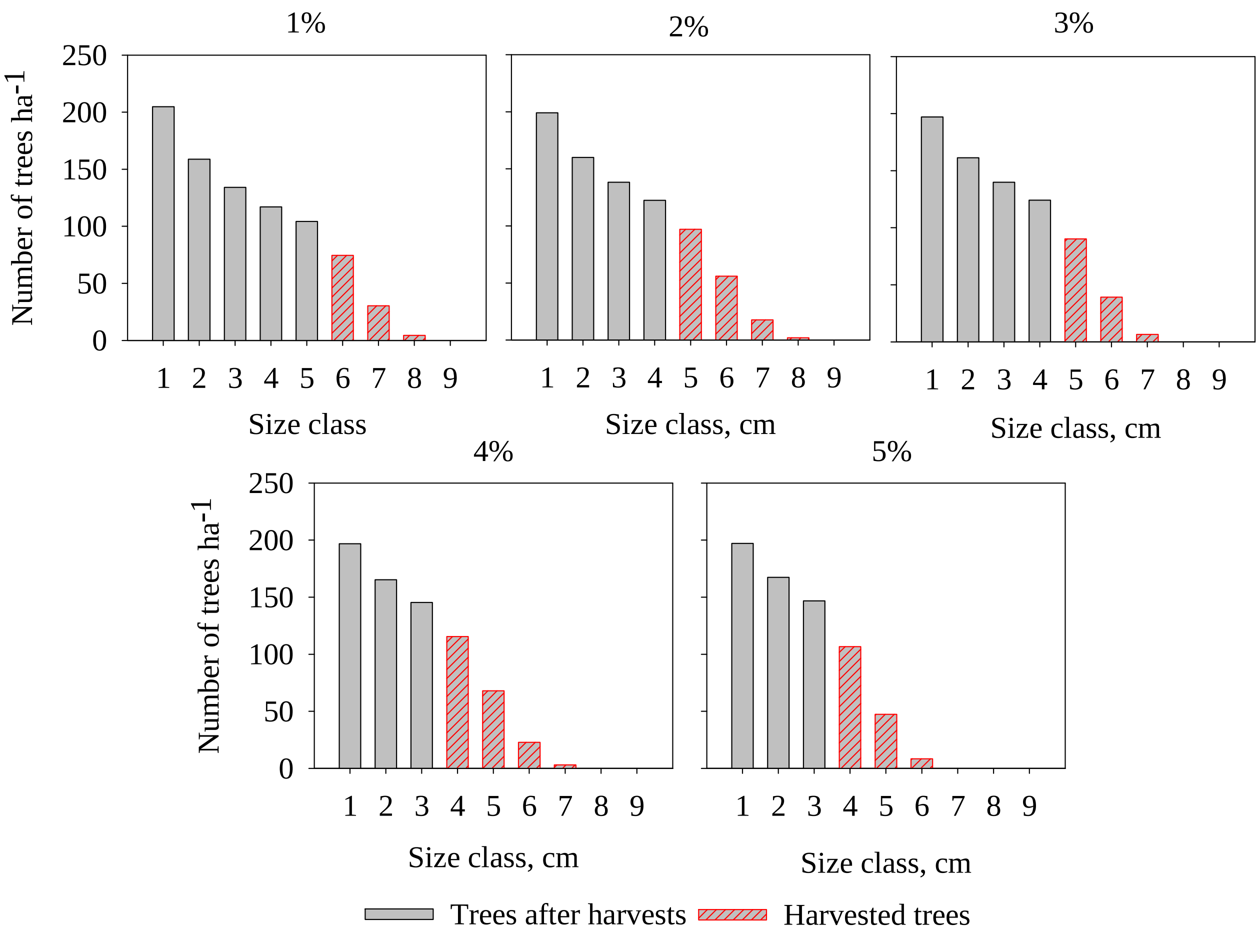


Figure 3: Stand structure and harvested trees in steady state with interest rates 1% - 5%, with 300€ fixed cost. Size classes begin at 7.5cm and increase in 5cm increments.

Effect of interest rate

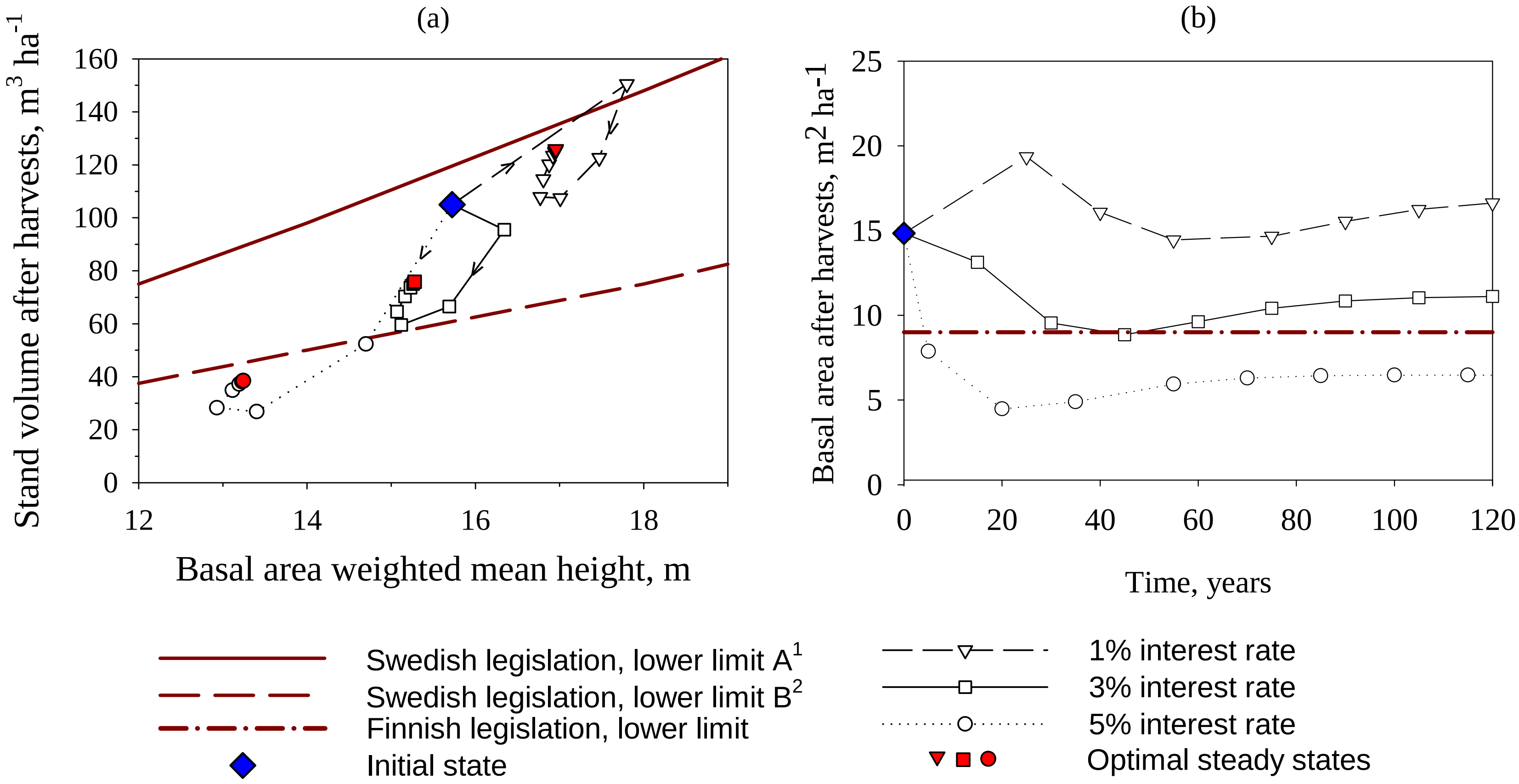
Younger even aged stand			Interest rate		
Harvest	**1 %**	**2 %**	**3 %**	**4 %**	**5 %**
1	20	15	10	5	0
2	35	35	25	25	15
3	50	55	40	45	30
4	70	75	65	65	50
5	85	95	80	85	65
Steady state interval	15	20	15	20	15

Uneven-aged stand			Interest rate		
Harvest	**1 %**	**2 %**	**3 %**	**4 %**	**5 %**
1	0	5	0	0	0
2	10	25	15	20	15
3	25	45	30	40	30
4	40	65	55	60	45
5	55	85	70	80	60
Steady state interval	15	20	15	20	15

Times of transition harvests and steady state interval from different initial states with interest rates of 1%-5% and 300€ fixed cost

cf. Faustmann: Higher interest rate results in shorter rotation

Optimal solutions compared to legal limitations



Optimal solutions compared to (a) Swedish and (b) Finnish forest legislation

Note: fixed harvesting cost €300, initial state a young even-aged stand

[1]Should not be violated without a special permission

[2]Violation implies an artificial regeneration obligation

Conclusions

- Bilevel optimization produces a coherent picture of optimal uneven-aged management
- Including the harvest timing in optimization is crucial

- Same steady state solution regardless of initial state of the stand
- Increasing fixed harvesting costs postpones harvests and lengthens steady state interval
- Increasing interest rate decreases physical yield, average stand density and the size of harvested trees, but steady state interval may lengthen or shorten

Thank you for your attention!

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