Optimal rotation sequence of Norway spruce in a changing climate

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Introduction – background

- Typical approach to optimizing rotations:
  - Fixed parameters: volume growth, price, interest rate, etc.
  - Find a harvesting schedule that maximizes bare land value

- This is the classic Faustmann model (Faustmann 1849, Samuelson 1976)
  - Optimal solution: a sequence of identical rotations

- The approach is not valid if (any of) the parameters change over time.
  - Optimal solution: a sequence of **un**identical rotations

Introduction – objective & solution concept

- We optimize the management of a Norway spruce stand in a changing climate
- The stand is used for timber production and climate change mitigation

- Climate change alters growing conditions
- Climate policy changes
  - e.g. the socially optimal price for carbon changes

- **Thus**: The optimal solution is a sequence of **un**identical rotations

Introduction – research questions & results

- How is the optimal clearcutting age determined?
- How does it change over time?
  - Special focus on how **carbon** and **albedo regulation** affect the optimal rotation
- Analytical results:
  - We provide optimality conditions (continuous time)
  - We present an algorithm for solving the problem (discrete time)
- Numerical results:
  - We solve the sequence of optimal rotation sequence in Kuusamo, Northern Finland
  - Climate change and climate policy are synchronized with a global scenario produced using DICE 2013R (Nordhaus & Sztorc, 2013)

Introduction – previous literature

- Optimal rotation with
  - Carbon: van Kooten et al. (1995)
  - Carbon and Albedo: Thompson et al. (2009)
- Pricing of radiative forcing (Social Cost Forcing, SCF): Lutz & Howarth (2014), Rautiainen & Lintunen (2017)

- Changing conditions
  - Basics: Chang (1998)
  - Decreasing discount rate: Price (2011, 2017), Brazee (2018)
  - Increasing carbon price: Ekholm (2016)
  - Changing growing condition: Pihlainen & Tahvonen (2017)

Introduction – previous literature

	Climate change affects growth	Carbon and albedo included	Consistent pricing of carbon and albedo	Increasing carbon price	Changing rotation length	Declining interest rate	Synchroni-zation with global climate scenario	Species selection or species mix optimization
Chang (1998)*	•				•	•		
Ekholm (2016)				•	•			
Lutz & Howarth (2014)		•	•	•		•		
Lutz & Howarth (2015)		•	•	•		•		
Lutz et al. (2016)		•	•	•		•		
Matthies & Valsta (2016)		•						•
Pihlainen & Tahvonen (2014)	•				•			
Brazee (2017)					•	•		
Thompson et al. (2009)		•						•
This study	•	•	•	•	•	•	•	

Assumptions

- Notation:
  - Timber grade, i, volume growth $g_i(a,t)$
  - SCC: $p_C(t)$ *"i.e. carbon price"*
  - SCF: $p_F(t)$ *"i.e. albedo price"*
  - Interest rate: $r(t)$
  - Timber grade price: $p_i(t)$
- Steady state after time T, i.e. values are constant when $t \geq T$
- Timber grade volume:
  - $v_i(a,t) = \int_0^a g_i(\tilde{a}, t - a + \tilde{a}) d\tilde{a}$
- Discount factor between t and $t + s$:
  - $\beta(t,s) = \exp\left(-\int_0^s r(t+u)du\right)$

NPV of one rotation

- $\Pi(a_i, t_i)$ is the NPV of profits over one rotation. It contains:
  - Regeneration cost at the beginning of rotation: $-C$
  - Income from final harvest: $\beta(t_i, a_i)\, F_n(a_i, t_i + a_i)$
  - and thinning: $\sum_{j=1}^{n-1} \beta\big(t_i, a_j(t_i)\big) F_j \left(a_j(t_i), t_i + a_j(t_i)\right)$
  - Net subsidies: $\int_0^{a_i} \beta(t_i, a) S(a, t_i + a) da$
- In this paper we have exogenous thinning management, i.e., the sequence of thinning ages $a_j(t_i)$
- Harvest net-revenues:

$$F_j(a,t) \coloneqq \left[\sum_g p_g(t) w_g(a,t) - c_j\right] h_j v(a,t) - p_c(t)\Sigma(a,t) + \lambda^{HWP}(a,t) + \lambda^{RES}(a,t)$$

- The climate policy net-subsidies, $S(a,t)$, consist of three terms:

$$S(a,t) = p_C(t)\sigma(a,t) + \lambda^{LIT}(a,t) - p_F(t)\alpha(a,t)$$

Optimization problem

- Objective: Maximize net present value of net-revenues (i.e. bare land value)
  - Perfect foresight
- Separate maximization problem for each moment t_0
  - Sequence of harvest ages: $\boldsymbol{a} = [a_0, a_1, \ldots]$
- Bare land value at period t_0

$$LEV(t_0) \coloneqq \max_{\boldsymbol{a}} \sum_{i=0}^{\infty} \beta(t_0, t_i - t_0)\Pi(a_i, t_i)$$

where $t_{i+1} = t_i + a_i$. Rewriting, we obtain the Bellman equation:

$$LEV(t_0) = \max_{a_0}\{\Pi(a_0, t_0) + \beta(t_0, a_0)LEV(t_0 + a_0)\}$$

- This structure is valid for all rotations and calendar times

When to clear-cut a stand?

- Noting that for all t_i:

$$LEV(t_i) \coloneqq \max_{\boldsymbol{a}}\{\Pi(t_i, a) + \beta(t_i, t_i + a)LEV(t_i + a)\}$$

- The first order condition for optimal rotation length, a, is

$$\frac{\partial}{\partial a}F_n(a,t) + \frac{\partial}{\partial t}F_n(a,t) + S(a,t) + LEV'(t) = r(t)[F_n(a,t) + LEV(t)]$$

New terms!

Solution algorithm

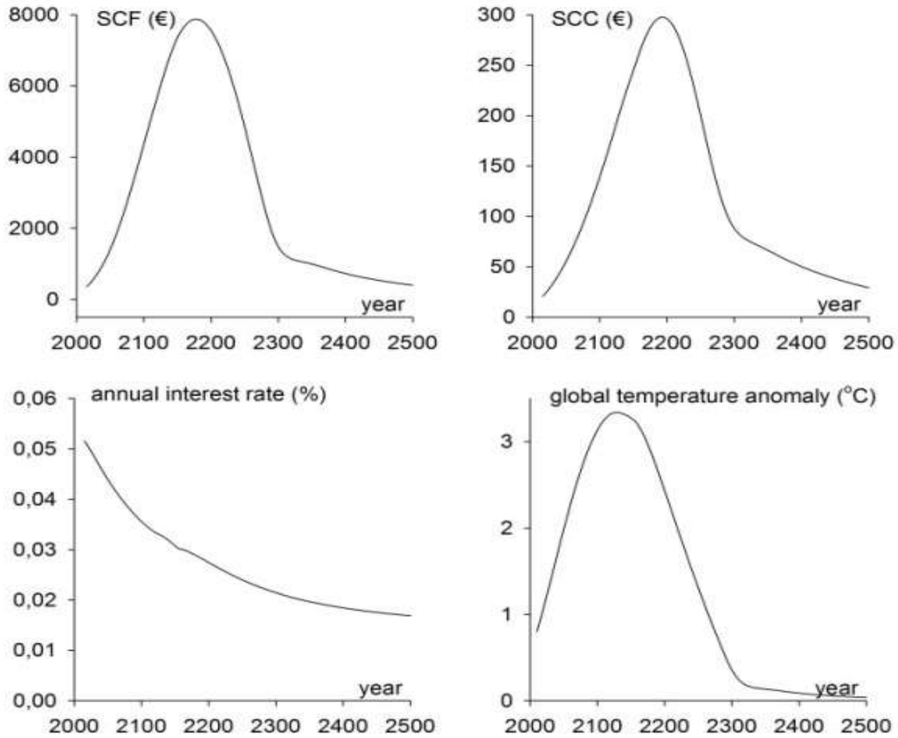
- Backward induction:
  1. For $t = T$, solve the steady-state problem.
     Since after calendar time T the parameters of the model are time-invariant, $LEV(T) = LEV(T + a)$, for all $a \geq 0$. Thus, we can reformulate the problem as a Hartman problem and solve it accordingly. The solution yields land values $LEV(T + a)$, for all $a \geq 0$. Finally, set $s = 1$.
  2. For $t = T - s$, solve the time-variant problem.
     This can be done directly as step 1 solved values of $LEV(T + a)$, for all $a \geq 0$.
  3. Increase s by 1.
     If $s > T - t_0$, end, otherwise go back to step 2.

Numerical examples – data & assumptions

- Time paths of key parameters from DICE:
  - climate forcing price (Social Cost of Forcing, SCF)
  - carbon price (Social Cost of Carbon, SCC)
  - interest rate
  - global temperature anomaly
- Global temperature is scaled to local conditions and affects:
  - growing conditions
    - Changing growth modelled using Motti simulator
  - albedo (through snow cover)
- Stand-level analysis with exogenous timber prices
  - First, fixed timber prices, then with prices that correlate positively with the SCC

Data and assumptions

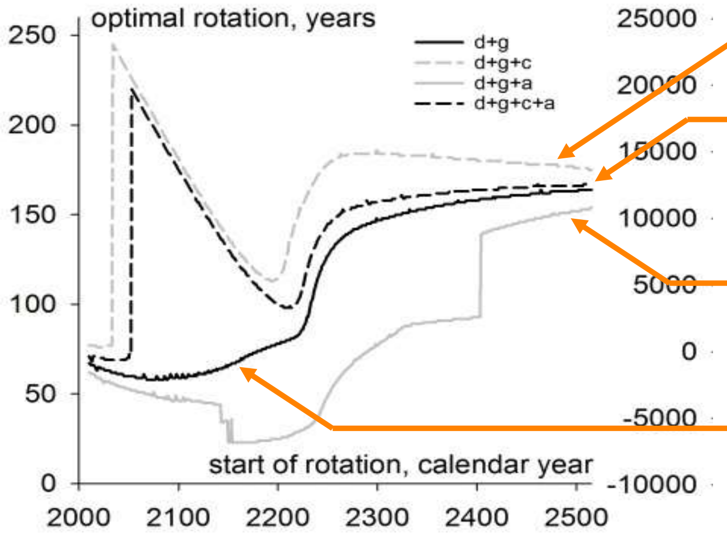
$€\,(Wm^{-2}yr)^{-1}$ $€t_{CO2}^{-1}$



Very high prices!
Let's use ¼.

Results – optimal rotation and LEV

d = discounting; g = growth; c = carbon; a = albedo;



Carbon pricing (alone) lengthens rotations.

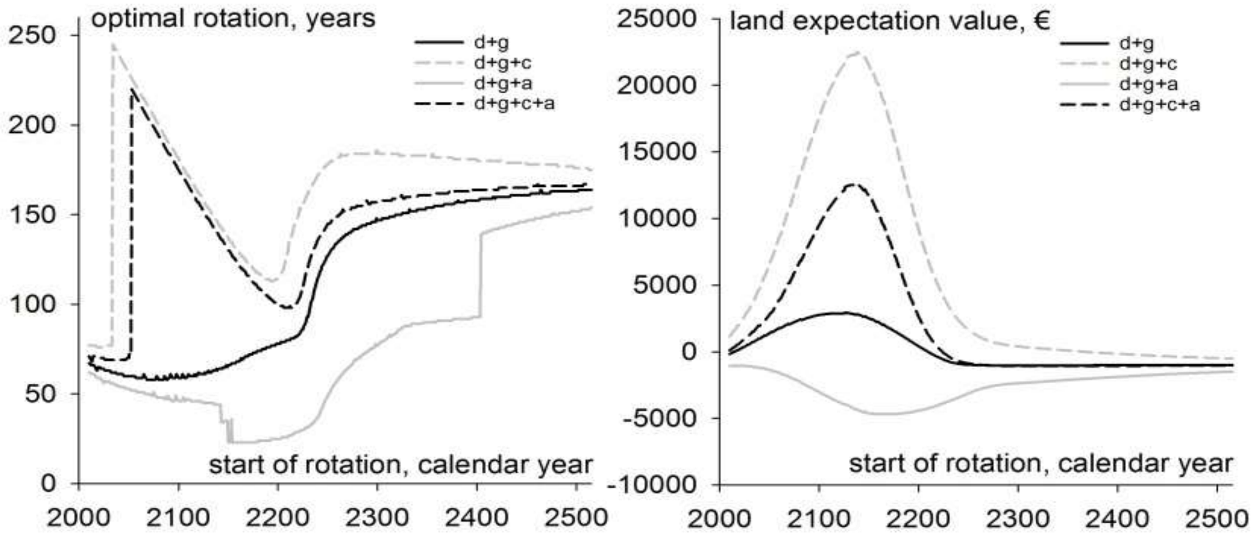
Regulating carbon & albedo:
- carbon pricing has stronger impact
- albedo softens the impacts

Albedo pricing (alone) shorthens rotations.

No climate policy.
In the beginning: Improving growth conditions & declining interest rate cancel out each other's effects

Results – optimal rotation and LEV

d = discounting; g = growth; c = carbon; a = albedo;



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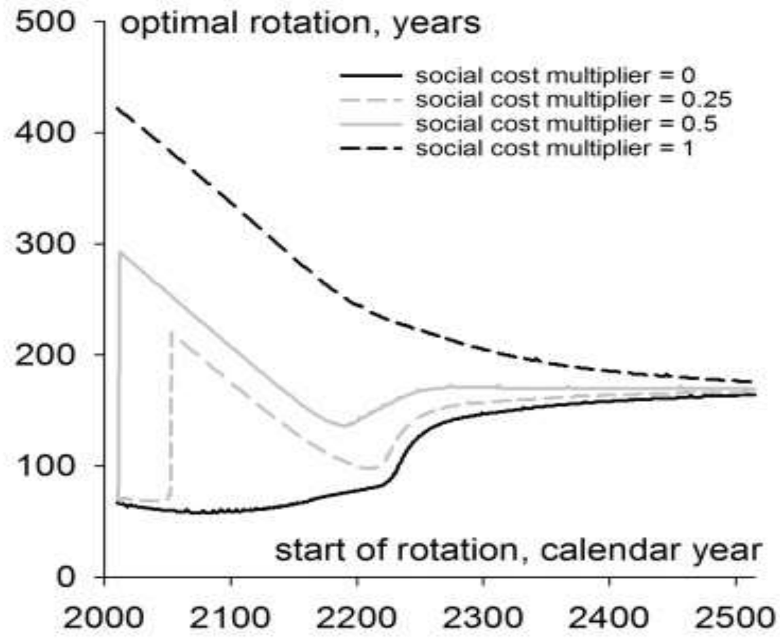
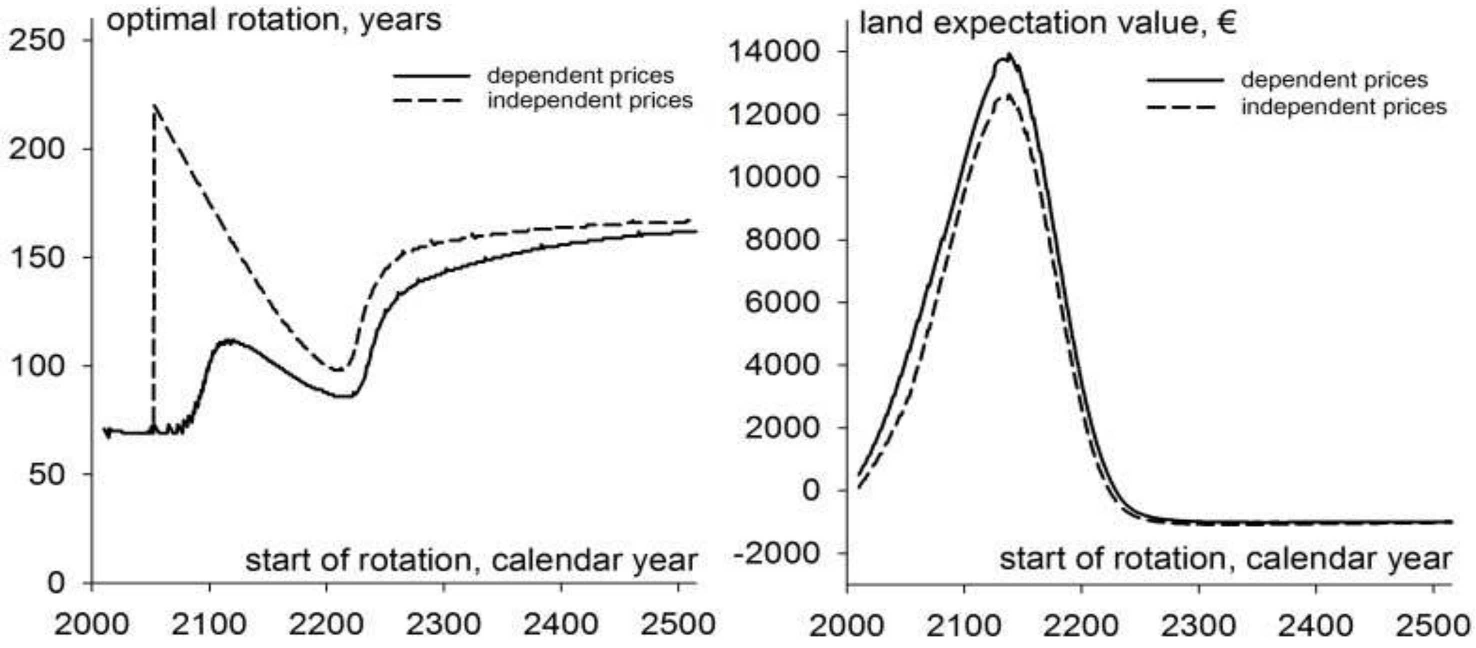
Results – the effect of scaling up SCF & SCC



Results – timber prices increasing with SCC



Conclusions

- The optimal solution is a (changing) rotation sequence
  - The solution method reduces back to the Faustmann model if parameters are time-invariant
- Improved growth conditions shorten the rotation and decreased interest makes the rotation longer
- Carbon pricing has a stronger effect on rotation than corresponding albedo pricing at least in conditions of Northern Finland
- High carbon and albedo prices reduce clearcutting incentives (i.e. high increase in clearcutting age)
- If timber prices increase with the carbon price, the increase of the clearcutting age is more moderate

Thank you!

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What is the focus of your research and why is it important for climate, bioeconomy or people?
We focus on the optimization of the even-aged management of a Norway spruce stand for timber and climate benefits in a changing climate.

Did your research identify key challenges (threats or risks) to maintain the critical values of boreal and mountain ecosystems?
Young Norway spruce stands store little carbon but have a higher albedo than older carbon-rich stands. Thus, from a climate change mitigation point-of-view, there is a trade-off between the cooling impact of increased carbon storage and the warming impact of decreased albedo, especially in the boreal region.

What would be your suggestion to address these challenges?
The challenge can be addressed by jointly optimizing forest management for timber and climate benefits (which are obtained by regulating carbon storage and albedo).

Appendix

Results – the first three rotations