Optimal forest species mixture with carbon storage and albedo effect for climate change mitigation

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Background: Climate Change Mitigation

Atmosphere

Photo-synthesis

CO₂

Forest

Harvest

Photo: Juha Aalto
More Refined Picture

Photo: Juha Aalto

Forest management

Photo-synthesis

CO₂

Avoided emissions

Carbon storage

VOCs

Albedo

Biomass accumulation

Time

Atmosphere

Forest
Some studies (Betts, 2000; Jackson et al., 2008; Lohila et al., 2010) claim that afforestation in boreal regions creates a warming impact due to albedo loss.

Also Thompson et al. (2009) and Sjølie et al. (2013) analyzed the albedo impact but not in mixed stands.

In pure stands, broadleaved forests have shown to have benefits over conifers in total climatic impacts (Nikinmaa et al., 2015).
Goals

- Analyze the mixtures of Norway spruce and silver birch in terms of their different ecosystem services including timber returns, carbon storage value and albedo effect
- Build an optimization model for Ecosystem Services Expected Value (ESEV)
- Find out the optimum management for the mixture
- Explore parameter uncertainties involved
Ecosystem Service Setup

- The analysis covered
  - Timber production
  - Carbon storage in the forest ecosystem
  - Albedo effect on radiative forcing
- Time preference was included as a discount rate
- Carbon offset price was used for valuing carbon storage
- Albedo effect was first computed as radiative forcing and then translated into CO2 units (and offset price)
Even-aged, Mixed Stand Dynamics

• Stand growth model by Mielikäinen (1985) for Norway spruce (P. Abies) and Silver birch (B. pendula) even-aged mixtures
  • Growth of birch is independent of spruce volume
  • Growth of spruce is reduced by increasing birch
  • At early age, birch grows faster than spruce
  • Later, spruce grows faster than birch
Figure 0. The optimal species composition (per cent of stand volume) when maximizing mean annual increment. (Valsta 1988)
Carbon and Albedo Valuation

- Ecosystem carbon storage
  - Stem volume by species
  - Biomass expansion factors (Lehtonen et al. 2004)
  - Carbon offset prices 0, 20, 40, 100€ ton CO$_2$\(^{-1}\)
- Albedo radiative forcing
  - Bare land is the baseline
  - Increasing stem volume reduces albedo $\rightarrow$ warming
  - Full stocking at 100 m$^3$/ha (satellite data)
  - Spruce: 11.865 W m$^{-2}$, Birch: 6.388 W m$^{-2}$ (Kuusinen et al. 2014)
  - 1 W m$^{-2}$ forcing compares to 11.0 ton CO2 ha$^{-1}$ in the atmosphere (Akbari et al. 2009)
Example of the Magnitude of the Albedo Effect

• Carbon storage
  • Spruce stand stem volume of 200 m$^3$ ha$^{-1}$
  • BEF 0.79
  • Biomass 158 ton ha$^{-1}$, carbon 79 ton ha$^{-1}$
  • Carbon storage is 290 ton CO2 ha$^{-1}$

• Albedo effect
  • Forcing compared to bare land 11.8 W m$^2$
  • 1 W m$^{-2}$ forcing compares to 11.0 ton CO2 ha$^{-1}$
  • Note: also smaller magnitudes have been suggested
  • Albedo effect is 130 ton CO2 ha$^{-1}$
Value Function Formulation
(Ecosystem Service Expectation Value)

\[
\max \pi = \left[ \sum_{t=0}^{T} h_t (1 + r)^{-t} - w + \sum_{t=0}^{T} cr_t (1 + r)^{-t} - \sum_{t=0}^{T} a_t (1 + r)^{-t} \right] \frac{1}{1 - (1 + r)^{-T}}
\]

Where
\[\pi = \text{Ecosystem Service Expectation Value (ESEV)}\]
\[h_t = \text{net harvest income at year } t\]
\[w = \text{regeneration costs}\]
\[cr_t = \text{credits for carbon storage at year } t\]
\[a_t = \text{albedo cost (relative to bare value) at year } t\]
\[r = \text{interest rate}\]
\[T = \text{rotation length}\]
Solution Method

- Variables to be optimized are
  - Young stand species composition
  - Intermediate harvests (time, intensity, species composition)
  - Final harvest timing
- The optimum solution contains
  - Optimum stocking by species and # of trees over time
  - Discrete-time, discrete-state dynamic programming based on forward recursion

\[
R(x_{t+1}) = \max \{H(x_{t+1}, x_t) + C(x_{t+1}, x_t) + A(x_{t+1}, x_t) + R(x_t)\}
\]

\[
\text{subject to } t = 1, \ldots, T
\]
Results

- The effects of including the albedo forcing (in addition to carbon storage) were
  - Birch stands gained in ESEV relative to spruce
  - Share of birch in stocking generally increased
  - Optimum rotation was mostly unchanged
Table 3. Ecosystem service rents that form the objective function in Equation 1 organized by ecosystem service and percentage of silver birch in the stand. Values are taken from the results reported in Fig. 2 and correspond to different average birch values for the whole rotation. Climate benefits are reported using a 3% discount rate, an intra-species albedo parameter difference of 5.477 W m⁻² and a baseline climate offset price of 20€ ton CO₂⁻¹.

<table>
<thead>
<tr>
<th>Silver birch in the stand (%)</th>
<th>Rotation Age</th>
<th>Ecosystem Service Expectation Values (ESEV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Timber ESEV</td>
</tr>
<tr>
<td>0</td>
<td>85</td>
<td>5015</td>
</tr>
<tr>
<td>17</td>
<td>85</td>
<td>5085</td>
</tr>
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<td>24</td>
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<td>3911</td>
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<td>74</td>
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<td>3299</td>
</tr>
<tr>
<td>83</td>
<td>85</td>
<td>3005</td>
</tr>
<tr>
<td>93</td>
<td>85</td>
<td>2593</td>
</tr>
</tbody>
</table>
Results

- The effects of including the albedo forcing (in addition to carbon storage) were:
  - Birch stands gained in ESEV relative to spruce
  - Share of birch in stocking generally increased
  - Optimum rotation was mostly unchanged

- Increasing carbon offset price:
  - Increased the share of birch
  - Increased the optimum rotation
  - Removed the shortening effect of increasing interest rate
Fig. 1. Average percent of silver birch over the entire rotation for increasing climate offset prices (€ ton CO₂⁻¹) and increasing differences in albedo forcing (W m⁻²) between Norway spruce and silver birch. Where a) is the value at a discount rate of 1%, b) at 3%, and c) at 5%.
• When timber returns was ignored, the “climate only” ecosystem service maximization led to a birch dominated stand
Fig. 2. Percent of silver birch in the stand over the rotation until the optimal rotation is reached for increasing climate offset prices (€ ton CO\textsubscript{2} \textsuperscript{-1}) at an albedo difference 5.477 m\textsuperscript{3} ha\textsuperscript{-1} for spruce over birch, discount rate of 3\%, and consideration for offsets at a price of 100€ ton CO\textsubscript{2} \textsuperscript{-1} with no timber stumpage (i.e. climate only). Albedo difference between species is based on empirical results from Kuusinen et al. (2014).
Results, cont’d

• When timber returns was ignored, the “climate only” ecosystem service maximization led to a birch dominated stand

• Difference in species albedo forcing had to be around 4 W m⁻² to markedly change the optimum species composition
Fig. 3. Percent of the silver birch in the stand until 100 years at decreasing levels in the difference in albedo forcing (W m⁻²) between Norway spruce and silver birch at a climate offset price of 100 € ton CO₂⁻¹ and an albedo saturation point of 60 (m³ ha⁻¹) and discount rate of 3%.
Table 3. Stand summary statistics for a sample management regime at an offset price of 20€ ton CO$_2$$^{-1}$, a 5W m$^{-2}$ difference in albedo forcing, and 3% discount rate. Percent of Birch refers to the percent at that age.

<table>
<thead>
<tr>
<th>Age (Years)</th>
<th>Volume (m$^3$ha$^{-1}$)</th>
<th>Percent of Birch (%)</th>
<th>Number of Trees</th>
<th>Volume per Tree (m$^3$ha$^{-1}$stem$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>208.67</td>
<td>1.09</td>
<td>219</td>
<td>0.95</td>
</tr>
<tr>
<td>80</td>
<td>258.10</td>
<td>0.90</td>
<td>318</td>
<td>0.81</td>
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<td>75</td>
<td>342.70</td>
<td>0.72</td>
<td>489</td>
<td>0.70</td>
</tr>
<tr>
<td>70</td>
<td>323.79</td>
<td>5.57</td>
<td>522</td>
<td>0.62</td>
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<tr>
<td>65</td>
<td>320.21</td>
<td>14.93</td>
<td>596</td>
<td>0.54</td>
</tr>
<tr>
<td>60</td>
<td>273.09</td>
<td>13.88</td>
<td>596</td>
<td>0.46</td>
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<td>55</td>
<td>225.00</td>
<td>12.75</td>
<td>596</td>
<td>0.38</td>
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<tr>
<td>50</td>
<td>238.61</td>
<td>11.57</td>
<td>796</td>
<td>0.30</td>
</tr>
<tr>
<td>45</td>
<td>186.74</td>
<td>10.21</td>
<td>796</td>
<td>0.23</td>
</tr>
<tr>
<td>40</td>
<td>137.34</td>
<td>8.82</td>
<td>796</td>
<td>0.17</td>
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<tr>
<td>35</td>
<td>91.52</td>
<td>7.44</td>
<td>796</td>
<td>0.12</td>
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<td>30</td>
<td>71.19</td>
<td>6.20</td>
<td>1108</td>
<td>0.06</td>
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<tr>
<td>25</td>
<td>52.00</td>
<td>5.00</td>
<td>1800</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Conclusions

• We derived optimum management for two-species spruce-birch mixed stands containing three ecosystem services (timber income, carbon storage, albedo forcing)
• The admixture of birch was always optimal
• For base parameter values, spruce was the dominant species with some 10-30% birch
• For climate only services birch was the dominating species
• The amount of optimum admixture was dependent on parameter value assumptions
Thank you for your interest!
References


Figure X. The maximum M.A.I. in relation to species composition of the total volume production during the rotation. (Valsta 1988)