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Title: Mitigating forest biodiversity and ecosystem service losses in the era of bio-based economy

Year: 2018

Version: Accepted version (Final draft)

Please cite the original version:

Eyvindson, K., Repo, A., & Mönkkönen, M. (2018). Mitigating forest biodiversity and ecosystem service losses in the era of bio-based economy. Forest Policy and Economics, 92(July), 119-127. https://doi.org/10.1016/j.forpol.2018.04.009

Appendix 2 – Enumeration of Solutions where for Expected value.

When conducting multi-objective optimization, including all features of the problem which are of interest to the decision maker is of the utmost importance. In the model developed in the main text, those features were evaluated by monitoring indicators of the optimized plan. If we choose to ignore an indicator, there is an implicit assumption of disinterest, and any value for that ignored indicators is acceptable. If included into the problem formulation, solutions may exist which the indicator may be improved without causing any negative changes to all other aspects of interest.

To be able to compare the optimized solution where all indicators of interest are included in the problem formulation to the case where only one indicator is included in the problem formulation requires the enumeration of a suitable subset of possible solutions. In this case, we are searching for a comprehensive subset of the solutions which provide a specific quantity of even-flow harvesting income.

To generate a large subset of unique solutions to the problem, the model should allow for some way of explore the subsets in a systematic fashion. To do this, we first examined the solutions provided by the optimized solutions were all indicators were used (Model 2 from the main text) and there were three key forest management regimes (Set Aside (*SA)*, Business as Usual (*BAU*) and Continuous Cover Forestry (*CCF*)) used in the optimized solutions. The model that follows is developed to explore the range of combinations of the three management regimes in the provision of a specific quantity of harvested income. The model detailed here incorporates weighted goal programming (Tamiz and Jones 2010) to explore the decision space:

Model:

[A-1] $$\min \sum_{m\in\{CCF,BAU\}} (n_m + p_m) - e\sum_{k=1}^{K} x_{kSA}$$

Subject to

[A-2] $$\sum_{k=1}^{K}\sum_{j=1}^{J_k} c_{kj1}x_{kj} \leq \sum_{k=1}^{K}\sum_{j=1}^{J_k} c_{kji}x_{kj}\,, i = 2, \dots, I$$

[A-3] $$\sum_{k=1}^{K}\sum_{j=1}^{J_k} c_{kj1}x_{kj} \geq z * f$$

[A-4] $$\sum_{k=1}^{K} x_{km} - p_m + n_m = \left(r_m^f - s_m^f\right)v_m + s_m^f, m = \{CCF, BAU\}$$

[A-5] $$\sum_{j=1}^{J_k} x_{kj} = 1, k = 1, \dots, J$$

[A-6] $$x_{kj} \geq 0 \forall k = 1, \dots, K, j = 1, \dots, J_k$$

where p_m and n_m are the positive and negative deviations from the target quantity of area managed by the selected management regime, x_{kj} is the decision to manage stand *k* according to management regime *j*, *e* is a small positive value used as an augmentation value (Wierzbicki, 1986) to maximize the quantity of area managed according to *SA*, subject to the other aspects of the optimization model, $c_{kjt}$is the value of the timber available from stand *k* according to management regime *j* at the t^{th} period, *z* is the objective value of model 1 of the main text, *f* a parameter which is set to determine the percentage of maximum periodic timber harvest is required, v_m is a parameter which is set to a proportion within the range of 0-1, to allow exploration of the range of solutions, r_m^f and s_m^f are respectively the maximum and minimum quantities of management regime *m* possible while still having the potential of meeting the required harvest income level constrained by the parameter *f*. These values were evaluated using a separate linear program. In this way, constraint [A-4] is a goal programming constraint, where the target is a value between the maximum and minimum value for the particular management regime. The specific targets were derived by a systematic approach, we set v_{CCF} and v_{BAU} to value between 0 and 1 with intervals of 0.05, and solved for each combination of these values (thus a total of 441 optimizations). In summary, the objective function is to strive to find a solution which manages the forest with as near to the specific targets for both *CCF* and *BAU* management regimes, while ensuring a constant flow of timber income. The augmentation term promotes the use of the management regime *SA* when possible.

To find the maximum and minimum possible quantities of management regimes (r_m^f and s_m^f)the following models were used:

[A-7] $$\max r_m^f = \sum_{k=1}^{K} x_{km} \ or \min s_m^f = \sum_{k=1}^{K} x_{km}$$

subject to [A-2], [A-3], [A-5] and [A-6].

To explore the decision space of the solutions which can meet the constraints of providing an even-flow of timber at a specific target, we systematically modified the parameter v_m for both the management regimes *CCF* and *BAU*. As stated earlier, we decided to focus our exploration on solutions which utilized a combination of *CCF*, *BAU* and *SA*. We believe that this is justified as these are the key management regimes from the optimal solution. To explore the entire range of solutions with all 19 management regimes would require considerable computational resources as the total number of potential solutions would be an exceptionally large number.

By modifying the parameters of only three management regimes, a total of 441 iterations were run to examine the decision space. For the management regimes *CCF* and *BAU* the parameter v_m was set to range from 0 to 1 using an interval of 0.05. This provided a 21 x 21 frame for the targets of CCF and BAU. Through the augmentation value, the *SA* management regime was always promoted over the use of all other management regimes, while the set of constraints ensured achievement of the required harvest target. The use of goal programming allows all solutions to be feasible, depending on the targets selected; some of the solutions may be the same. To ensure appropriate accounting, only solutions which differed by greater than 0.5% in the management regimes selected were used in the remaining analysis.

To provide a description of the range of solutions, figure S1 highlights the solutions for each of the harvest level targets. The distribution of results can be seen in the figure for each of the indicators used in the study. For the indicator "Income", there is no fluctuation from the required target, as the constraints prevent either positive or negative deviations from the target. By examination of the distribution of the remaining indicators in the figure, we can be rather confident that the range of solutions appropriately covers the decision space. Thus, the set of solutions can be used as an approximation of what can occur without optimization for all indicators simultaneously. Some of the indicators do have values larger than the optimized solution where all indicators are considered. However, this does not mean that the solution is 'better' than the optimized solution. To make that comparison, all indicators need to be analyzed together, and it would be extremely likely that the set of indicators would indicate a clear improvement.

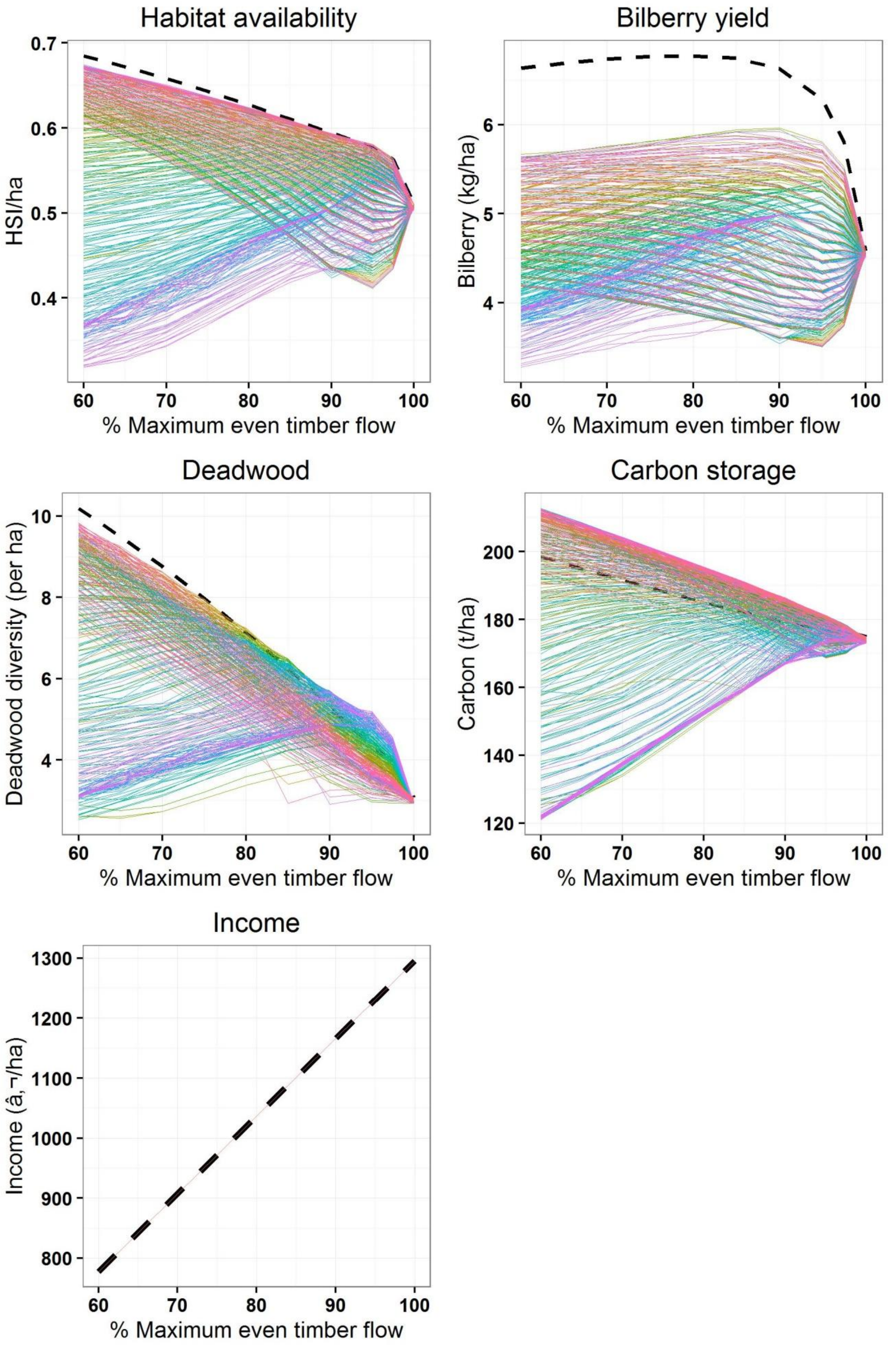
Habitat availability
HSI/ha
0.7
0.6
0.5
0.4
60
70
80
90
100
% Maximum even timber flow
Bilberry yield
Bilberry (kg/ha)
6
5
4
60
70
80
90
100
% Maximum even timber flow
Deadwood
Deadwood diversity (per ha)
10
8
6
4
60
70
80
90
100
% Maximum even timber flow
Carbon storage
Carbon (t/ha)
200
180
160
140
120
60
70
80
90
100
% Maximum even timber flow
Income
Income (â,¬/ha)
1300
1200
1100
1000
900
800
60
70
80
90
100
% Maximum even timber flow

Figure S1. Representation of all scenarios produced to evaluate the expected results. All indicators are represented as per hectare values. The colored lines represent possible outcomes if only planning for income, while the thick black dotted line represents the solution where all indicators are included in the optimization.

References:

Jones, D. and Tamiz, M. 2010. Practical goal programming. Springer. New York. 170p.

Wierzbicki, A. P. 1986. On the completeness and constructiveness of parametric characterizations to vector optimization problems. OR Spectrum, 8(2):73-87.