International Journal of Wildland Fire 2018, **27**, 831–844
doi:10.1071/WF18041_AC

Supplementary material

The economic impact of fire management on timber production in the boreal forest region of Quebec, Canada

Baburam Rijal[A,D], *Frédéric Raulier*[A], *David L. Martell*[B] *and Sylvie Gauthier*[C]

[A]Centre d'Étude de la Forêt, Faculté de foresterie, de géographie et de géomatique, Université Laval, 2405 rue de la Terrasse, Québec, QC, G1V 0A6, Canada.

[B]Faculty of Forestry, University of Toronto, 33 Willcocks Street, Toronto, ON, M5S 3B3, Canada.

[C]Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du P.E.P.S., Québec, QC, G1V 4C7, Canada.

[D]Corresponding author. Email: baburam.rijal.1@ulaval.ca

Supplementary material 1. Timber harvest scheduling optimization model

This model aims to maximize the net present value from the sale of primary-processed products resulting from the processing of the harvested timber at the closest sawmill. Let,

Indices:

s stratum (1..S; S= 38, 52, and 66 in FMUs 026-65, 085-51 and 094-52, respectively),

a age class (1..30, 5-year intervals),

t period (1..30, 5-year periods),

p product (1..3; lumber, chips and sawdust),

Decision variables:

H_{sat} planned harvested area (ha) in stratum *s* and age class *a* during period *t*, ∀ *s*, *a* and *t*

X_{sat} area of age class *a* of stratum *s* at start of period *t* (ha), ∀ *s*, *a* and *t.*

Parameters:

x_{sa0} initial condition: area (ha) in stratum *s* in age class *a* in (ha), ∀ *s*, and *a,*

v_{sa} merchantable volume in stratum *s* in age class *a* (m^3 ha^{-1}) , ∀ *s* and *a*,

v_{psa} product volume (m^3 ha^{-1}), ∀ *p*, *s* and *a*,

a_s^{min} minimum harvest age (period), ∀ *s*,

b_f constant periodic burn rate,

d_s distance between the centroid of landscape unit to which a stratum belongs and the closest primary processing mill, ∀ *s,*

r_p product selling price at the delivery site for forest product *p* produced in the closest mill (\$ m^{-3}), ∀ *p*,

c^{fo} total costs incurred in the forest per unit of timber volume harvested (forest management, harvest, including loading timber) (\$ m^{-3}),

c_s^{tr} harvested timber transportation costs from harvest site to the processing mill (\$ m^{-3}),

c^{pr} product processing (*pr*) cost per unit of timber volume (\$ m^{-3}),

c_p^{tr} transportation cost (*tr*) from the processing mill to the product delivery site (\$ m^{-3}),

γ_t periodic discount factor ($(\frac{1}{1+r})^{5t-2.5}$) assumed to be applied at the mid point of the 5-year period, *r* being a discount rate (4% y^{-1}, BFEC 2013).

We maximized the net present value of the first two periods to maintain consistency with the strategic/tactical planning horizon of a sawmill (Gunn 2007; D'Amours *et al*. 2008). The objective function is structured in such a way that the policy model is vertically integrated with the sawmill responsible for costs, i.e., forest management, harvesting, transportation and processing costs, and its net present values are maximized, but abides with forest sustainability requirements by applying even flow of harvest volume constraints.

The objective function is therefore structured to maximize the net present value (NPV) from the sale of wood products processed at the closest primary processing mill as:

$$NPV_{Prod} = \max \sum_{t=1}^{2} \left[\gamma_t \sum_{p=1}^{3} \sum_{s=1}^{S} \left[\left(r_p - c^{fo} - c_s^{tr} - c^{pr} - c_p^{tr} \right) \sum_{a=a_s^{min}}^{30} v_{psa} \, H_{sat} \right] \right] \qquad [S1]$$

Constrained to:

Periodic even flow of harvest volume:

$$\sum_{s=1}^{S} \sum_{a=a_s^{min}}^{30} v_{sa} \, H_{sa(t-1)} = \sum_{s=1}^{S} \sum_{a=a_s^{min}}^{30} v_{sa} \, H_{sat}, \quad \forall \, t \in \{2..30\} \qquad [S2]$$

The planned harvest area is limited to be less than or equal to the area available in each stratum, age class and period, after accounting for the impact of fire with a constant periodic average burn fraction (b_f) by period over the planning horizon:

$$H_{sat} \leq (1 - b_f) X_{sat}, \quad \forall \, s, a \text{ and } t \qquad [S3]$$

Following Reed and Errico (1986), we also assumed that fire occurs uniformly and proportionally over all of the strata and the age-classes within each FMU. Accordingly, the area accounting constraints in Model III structure are given as:

in the youngest age class:

$$X_{s1t} = \sum_{a=1}^{30} H_{sa(t-1)} + b_f \sum_{a=1}^{30} X_{sa(t-1)}, \quad \forall\ s, a \text{ and } t \in \{2..30\} \qquad \text{[S4]}$$

in the upper collecting age class:

$$X_{sat} = (1 - b_f) \sum_{a=29}^{30} X_{sa(t-1)} - \sum_{a=29}^{30} H_{sa(t-1)}, \quad \forall\ s \text{ and } t \in \{2..30\} \qquad \text{[S5]}$$

and, in the intermediate age classes:

$$X_{sat} = \left(1 - b_f\right) X_{s(a-1)(t-1)} - H_{s(a-1)(t-1)}, \quad \forall\ s, a \in \{2..29\} \text{ and } t \in \{2..30\} \qquad \text{[S6]}$$

We used the mean of b_t (eq. 2) as the constant burn rate b_f required for our optimization model for each presuppression scenario. Although there were only 441 possible cases for random draws of two independent variables from a pool of 21 years of observations, 10 000 random draws were conducted for each presuppression scenario to generate the probability distribution function of b_t and achieve consistent estimations of the mean values (b_f).

Lumber has the highest value among the three products we used as the primary-processed products. Therefore, to avoid depleting the lumber resource with the lowest processing costs, we also added an even-flow constraint of lumber yield and an even flow of distance-weighted lumber yield:

$$\sum_{s=1}^{S} \sum_{a=a_s^{min}}^{30} v_{psa} * H_{sa(t-1)} = \sum_{s=1}^{S} \sum_{a=a_s^{min}}^{30} v_{psa} * H_{sat}, \quad p = \text{lumber}, \forall\ t \in \{2..30\} \qquad \text{[S7]}$$

$$\sum_{s=1}^{S} \frac{1}{d_s} \sum_{a=a_s^{min}}^{30} v_{psa} * H_{sa(t-1)} = \sum_{s=1}^{S} \frac{1}{d_s} \sum_{a=a_s^{min}}^{30} v_{psa} * H_{sat}, \ p = \text{lumber}, \forall\ t \in \{2..30\} \qquad \text{[S8]}$$

References

Bureau du forestier en chef (BFEC) 2013 Manuel de détermination des possibilités forestières 2013-2018. Gouvernement du Québec, Roberval, QC. Available at http://forestierenchef.gouv.qc.ca/wp-content/uploads/2013/01/MDPF_VF.pdf [verified 16 May 2017]

D'Amours S, Rönnqvist M, Weintraub A (2008) Using operational research for supply chain planning in the forest products industry. *Infor* **46**, 265–281.

Gunn E (2007) Models for strategic forest management. In 'Handbook of Operations Research in Natural Resources'. (Eds AJ Weintraub, JP Miranda, C Romero, T Bjørndal, R Epstein). (Springer, Heidelberg Berlin New York)

Reed WJ, Errico D (1986) Optimal harvest scheduling at the forest level in the presence of the risk of fire. *Canadian Journal of Forest Research* **16**, 266-278.

Supplementary material 2. Determination of the required number of simulations: coefficient of variation of the 5th, 50th and 95th percentiles of marginal net revenue between the two lowest presuppression expenditure scenarios ($0.40 and 0.60 ha^{-1} y^{-1}). The percentiles for each simulation sample size are constructed by 1,000 random draws from a pool of 1,500 simulations.