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Title: A Replanning Approach for Maximizing Woodland Caribou Habitat alongside Timber Production.

Andrew B. Martin^{1*}, Jonathan L.W. Ruppert¹, Eldon A. Gunn^{2†}, David L. Martell¹

¹*Faculty of Forestry, University of Toronto, 33 Willcocks Street, Toronto ON, Canada, M5S*

²*Department of Industrial Engineering, Dalhousie University, Halifax NS, Canada*

[†] Deceased

*corresponding author:

Andrew B. Martin
Eco Modelling Ltd.
73 Bathurst St. Suite 403
Toronto, ON, M5V 2P6
Telephone: 1-647-861-9100
Email: andrew@ecomodelling.co

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Abstract

We present a forest harvest scheduling model that meets timber harvest targets while maximizing a proxy measure of woodland caribou habitat based upon the configuration of preferred habitat on the landscape. Woodland caribou within the boreal forest region in Canada tend to prefer mature jack pine forest stands which tend to be rich in their preferred resource, lichen, and also reduce predation pressure. This can create conflict with industrial wood supply needs. We designed a model that can be used to identify good harvest scheduling plans given these competing objectives. Our approach is to use a series of sequential linear programming models that are solved within a replanning framework. Specifically, each individual linear programming model seeks to produce a solution that will meet timber harvest targets while minimizing the harvest of high quality woodland caribou habitat stands. Stands are assessed with respect to their suitability as woodland caribou habitat based on their contribution to the overall landscape Equivalent Connected Area (ECA), a combined spatial measure of preferred habitat amount and its connectivity. We used our model for a case study of the Trout Lake forest in northwestern Ontario, Canada, and found that our model creates approximately 10% more caribou habitat than an earlier heuristic procedure and 30% more caribou habitat than the prevailing woodland caribou habitat forest management plan in the Trout Lake forest while meeting the same timber harvest targets.

Introduction

Woodland Caribou conservation is an important forest management objective throughout Canada, including the province of Ontario. That importance is due largely to the fact that Woodland Caribou (*Rangifer tarandus caribou*), hereafter referred to as caribou, are listed as being threatened under the Species at Risk Act (SARA) (COSEWIC, 2000) because of recent range recession that has been observed within regions where industrial activities occur (Bergerud 1974; Environment Canada 2011). In response to this listing, the Ontario Ministry of Natural Resources and Forestry (OMNRF) has developed a spatial harvest scheduling plan, the Dynamic Caribou Habitat Schedule, which is often referred to as the *caribou mosaic*. One of the *caribou mosaic*'s objectives is to ensure that a specified amount of caribou habitat is maintained at all times across Ontario (OMNR 2014). Specifically, the *caribou mosaic* harvesting strategy was developed in response to the negative impacts of anthropogenic activities such as roads and harvesting, which have contributed to caribou range recession in Ontario (Bergerud 1974; Vors *et al.* 2007; McGreer *et al.* 2015). Its design reflects the need to address caribou habitat needs when developing strategic timber harvest plans and road building plans (OMNR 2014) as both timber harvesting and road building activities reduce the amount of preferred caribou habitat in a forest and increase the fragmentation of preferred habitat, making foraging and calving less successful due to the accompanying changes in the configuration and reduction in the amount of preferred resources (O'Brien *et al.* 2006; Thompson *et al.*, 2014). Moreover, Wittmer *et al.* (2005) and others have noted that anthropogenic activity facilitates the movement of boreal species of animals and alters the forest landscape to increase the amount of early seral forest that can potentially lead to increased predation pressure on caribou. This results from increases in early seral forest that promote increases in the abundance of white-tailed deer (*Odocoileus*

virginianus) and moose (*Alces alces andersoni*), which lead to subsequent increases in the abundances of predators such as black bears (*Ursus americanus*) and wolves (*Canis lycaon*) that will opportunistically prey on caribou.

Earlier research (Ruppert et al., 2016) found that the *caribou mosaic* is not optimal for joint planning of timber harvesting and caribou habitat conservation. The heuristic developed by Ruppert et al. (2016) (henceforth referred to as the *harvesting heuristic*) outperformed the *caribou mosaic* plan by maintaining 79% of the maximum possible amount of caribou habitat versus the *caribou mosaic* which maintained 60% of the maximum possible amount of caribou habitat. The maximum possible amount of caribou habitat is defined as the amount of caribou habitat measured using a no-harvest model over the same planning horizon and forest. To achieve that outcome, Ruppert et al. (2016) used a graph theory approach, where preferred habitat patches of caribou are nodes and potential movement paths for caribou are arcs connecting those nodes. Specifically, they measured caribou habitat using the Equivalent Connected Area (ECA) metric which is based upon the amount of preferred habitat patches and how well they are connected on the landscape (Saura et al., 2011). The ECA, which is based upon the spatial configuration of preferred stands, is computed by first classifying forest stands with respect to the quality of caribou habitat they provide. The classification scheme we used (which is described in Table 1) rates stands from 1 to 9 with 1 being the most preferred habitat (mature jack pine stands, rocky outcrops and shallow soil sites) and 9 being the least preferred habitat (stands near recently harvested areas, roads and utility corridors). Using this classification, potential movement paths are created using a cost surface (planning units assigned values in Table 1), whereby the potential movement of caribou or arcs are constructed to represent the least costly path between nodes (i.e., least-cost paths are a function of the distance

and additive costs of each arc along a cost surface) (Adriaensen *et al.* 2003; Fall *et al.* 2007). The ECA value for each forest stand is then computed based on the marginal contributions of individual patches of caribou habitat, determined from the simulation, to the overall habitat connectivity of the landscape (Ruppert *et al.*, 2016). Finally, a heuristic harvest value of each stand is calculated, which is a weighted function of the volume of merchantable wood in the stand were it to be harvested and the decrease in suitable habitat that might result were that to happen. This methodology allows one to attribute both the caribou habitat value and its potential timber harvest value (in terms of that caribou value and the amount of merchantable timber) to each forest stand, which can be subsequently used in heuristic and optimization approaches.

We utilize this caribou value for forest stands and advance the research of Ruppert *et al.* (2016) by developing an optimization framework that allows one to identify timber harvest schedules that provide a higher ECA value for the landscape than their *harvesting heuristic* while meeting the same timber harvest targets. We accomplish this by replacing the harvesting heuristic with a linear programming (LP) optimization model (Dantzig, 1963), and running that model repeatedly within a replanning framework. However, the non-linear spatial nature of the ECA metric makes it difficult to incorporate it directly in LP models. To deal with this non-linearity we incorporate the ECA calculations in a replanning framework. Replanning has been used in forest management planning in the past, particularly for dealing, for example, with uncertainty related to supply chain planning (Epstein *et al.*, 1999), and fire losses (Savage *et al.*, 2010). Specifically, in the replanning framework, LP models are run sequentially, each starting with its first period beginning at the start of the next period of the planning horizon, so the first LP model has its first period as period 1 of the planning horizon, the second LP has its first period as period 2 of the planning horizon, the third LP has its first period as period 3 of the

116 planning horizon, etc. After each LP model is solved, new ECA values are computed based on
117 the assumption that the first period harvests from the most recent LP model take place, and used
118 to update the LP for the next period.

119 Forest management planners have used strategic planning LP models to help balance
120 trade-offs between competing economic and environmental objectives for over 50 years (Gunn,
121 2007). Some of those that specifically addressed wildlife management include Bettinger *et al.*
122 (1997) who used Tabu Search to create contiguous blocks of habitat for Rocky Mountain Elk
123 (*cervus elephas nelson*). Bevers & Hof (1999) used an LP model to model population dynamics
124 to conserve habitat for species that have minimum inter habitat patch distance requirements
125 alongside timber harvesting. Another approach used by Gustafson *et al.* (2006) had two stages of
126 linear programming and a simulation model to first optimize timber harvesting and then assess
127 the quality of wildlife habitat that the optimized harvesting schedule produced. Öhman *et al.*
128 (2011) used stand neighborhoods in a mixed integer programming model to maximize hazel
129 grouse (*tetrastes bonasia*) habitat alongside timber harvesting in Northern Sweden. With respect
130 to woodland caribou, Schneider *et al.* (2012) applied optimization methods to determine
131 woodland caribou habitat reserves in Alberta, considering cost, industrial footprint, deer
132 presence, and climate change. However, timber harvesting was not central to their work. More
133 recently, Cui and Moore (2016) described a study in which the Ontario Ministry of Natural
134 Resources and Forestry used the spatially explicit Patchworks goal programming modelling
135 framework developed by Spatial Planning Systems¹ in conjunction with their own Zone
136 Delineation Tool to evaluate trade-offs involving goals associated with caribou habitat, road
137 construction and other values when delineating and specifying the timing of harvests to mosaic
138 blocks for the *caribou mosaic*.

¹ <http://www.spatial.ca>

Öhman et al.'s (2011) model is an example of a spatially explicit integer programming (IP) model. In spatially explicit IP models stands are represented by integer variables, and the spatial conditions being optimized are represented in the IP model as variables and constraints. This differs from our approach where continuous variables represent stands and the spatial conditions being optimized are represented by a proxy in our LP models. A spatially explicit IP model that integrated forest harvesting and ECA computations that could be solved to optimality would likely find better solutions than our approach; however, such a model would not be computationally tractable using today's technology. We find our approach to be necessary because the size of the forest we modelled is two orders of magnitude larger than those typically represented in spatial IP models, and spatial IP models become increasingly difficult to solve as problem size increases. For example, Öhman et al (2011) use 904 stands while our model uses 164,851 stands. More recently St. John et al. (2016) used an Optimal Corridor Construction Approach to create corridors of appropriate width and length while scheduling timber harvests with a spatially explicit IP model to develop habitat corridors for reindeer that were herded between two areas alongside timber harvests in a forest with 1996 stands.

Methods

Study area and harvesting strategies

Our analysis was carried out for the Trout Lake Forest Management Unit in Northwestern Ontario, Canada (Figure 1). We used Forest Resource Inventory (FRI) data from OMNRF, which was last updated in 2012. The FRI is an inventory of forest, ecological, and land use conditions that describes 555,000 square kilometers of Ontario's forest and wetlands (OMNR, 2009b). The Trout Lake Forest is an area of approximately 1 million hectares, where there are 164,851 square

forest stands at a size of 6.25 ha each that were created by Ruppert *et al.* (2016), so that a cost surface could be developed for our graph theory approach. Each stand is then classified as being one of 12 forest cover types that fall under 4 different silviculture regimes following current management plans for the Trout Lake Forest. More than 80% of the forest canopy is composed of both black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*).

We build upon some of the previous contributions to forest planning that address wildlife management by incorporating a graph theory framework into an LP model through the use of replanning methods. While the *harvesting heuristic* produces better ECA solutions than the current plan (*caribou mosaic*), the LP model embedded within a replanning framework bases harvesting decisions on more information than is available to the *harvesting heuristic*. The *harvesting heuristic* uses a myopic approach to specify which stands to harvest each period, one period at a time. For example, when it prescribes decisions to be implemented in period 1, it does not consider the impact of those decisions on harvesting decisions in period 2 or any other future period. By embedding an LP model in a replanning framework we can to some extent overcome this limitation, because it will incorporate consecutive harvests into harvesting decisions for each period.

Harvest scheduling LP model

To model the relationship between caribou habitat and timber production in the Trout Lake forest, we developed a Model I form of timber harvest scheduling LP model (Johnson & Scheurman, 1977) that identifies which stands to harvest in each period to meet the periodic harvest targets while maximizing a specified objective function. A Model I framework was used

because Model I maintains each stand’s spatial identity which is needed to measure the forest’s ECA. The structure of our LP model is as follows:

Sets

T : Periods

I : Stands

$J[i]$: Prescriptions that can be applied to stand $i \in I$

$H[t]$: Stand and prescription combinations, $(i, j): i \in I, j \in J[i]$, that are eligible for harvest during period $t \in T$

Z : Stand and prescription combinations, $(i \in I, j \in J[i]) \in H[1]$, that schedule the stand for harvest in period 1 where the stand will transition to a higher caribou habitat classification in period 2 if it is not harvested in period 1.

Parameters

$V[i, j, t]$: Volume of wood available for harvest from stand $i \in I$, managed under prescription $j \in J$, in period $t \in T$

$Eca[i, j, t]$: Measure of the ECA of stand $i \in I$, managed under prescription $j \in J[i]$, in period $t \in T$.

207

208 $Dist[i]$: Distance in meters of stand $i \in I$, from the nearest caribou habitat patch

209

210 $Target[t]$: The harvest volume target for period $t \in T$

211

212 $Area[i]$: Area of stand $i \in I$

213

214 $Hval[i, j, t]$: Heuristic harvest value of stand $i \in I$, managed under prescription $j \in J[i]$, in

215 period $t \in T$

216

217 **Variables**

218 $x[i, j]$: Area of stand $i \in I$ managed under prescription $j \in J[i]$

219

220 z : Total area of the stands harvested in period 1 that would transition to a higher caribou habitat

221 classification if they were not harvested during period 1. This variable only applies to period 1 of

222 each LP model.

223

224 The variable set $x[i, j]$ represents the area of stand i to be managed under silvicultural

225 prescription j , where a silvicultural prescription describes the management of a stand (e.g., the

226 timing and type of harvesting, regeneration, and silvicultural treatments) over the entire

227 planning horizon. All of our model prescriptions were generated using the prescription generator

228 described in Martin et al. (2016), and are either clearcut or “do nothing” prescriptions.

229

Objective

$$\text{Max} \sum_{\substack{t \in T \\ (i,j) \in H[t]}} Hval[i,j,t] * x[i,j] - \sum_{(i,j) \in Z} x[i,j] \tag{0}$$

The objective function (equation 0) is structured to maximize the harvest value of the harvested stands subject to a penalty for harvesting stands that will transition to a better caribou habitat classification category in the next period if they are not harvested. For example, if a Jack Pine stand is 57 years old in period 1 then it has a caribou habitat classification 4. If that stand is not harvested in period 1 it will be 64 years old in period 2, so it will have a caribou habitat classification 1 at that time, see Table 1. We penalize the harvesting of such stands in period 1 to discourage harvesting them by assigning a coefficient of -1 to the $x[i,j]$ variables where (i,j) belongs to Z in the objective function.

Constraints

$$\sum_{\substack{i \in I \\ j \in J[i]}} V[i,j,t] * x[i,j] = Target[t] \quad t \in T \tag{1}$$

$$\sum_{j \in J[i]} x[i,j] = Area[i] \quad i \in I \tag{2}$$

Equation 1 states that the volume harvested in each period must equal the harvest targets that the *caribou mosaic* must achieve for that period. Equation 2 describes the Generalized Upper Bound (GUB) constraints (Dantzig and Van Slyke, 1967), which state that no more than the total area of a given stand can be assigned to prescriptions.

$$Hval[i, j, t] = v[i, j, t] - \left(\frac{eca[i, j, t]}{1 + dist[i]} \right) \quad i \in I, j \in J[i], t \in T \quad (3)$$

Equation 3 defines the heuristic harvest value of a stand, *Hval*, as a function of the difference between the volume in a stand, and the stand's contribution to forest's ECA divided by that stand's distance from the nearest habitat patch (Ruppert et al., 2016).

We assume that following a harvest, stands regenerate with the same growth and yield attributes that they had prior to harvest. Stand mortality and stochastic disturbances (e.g., fire, insect, and storm damage) are not considered because the focus of this paper is a comparison of our optimization model with the *harvesting heuristic* which does not consider these events. Additionally, the development of spatial stochastic models would require a large undertaking in terms of development that is beyond the scope of this paper.

The ECA is a spatial attribute of a forest stand because it is based upon the connectivity of patches of caribou habitat in each period. For example, the contribution of each stand to the ECA of the forest depends on the attributes of that stand as well as the attributes of all the other stands on the landscape. At the same time, the contributions to ECA of all the stands around it in part depend on the attributes of that stand. This non linearity makes it impossible to use an LP model to optimize the ECA of the forest explicitly and that is why we optimize a proxy measure for a stand's contribution to ECA, its heuristic harvest value (Equation 4). We then integrate the heuristic harvest value into a replanning framework to compute the ECA of the forest at the end of every period. Figure 2 illustrates this framework.

The premise of the framework is as follows. We compute the ECA at the start of the planning horizon based on the initial state of the forest. We then incorporate the ECA values in our LP model for an 11 period planning horizon that begins in period 1, and solve it. The

solution to the LP model prescribes harvesting and silviculture actions for the entire planning horizon. We then use this solution to determine the predicted structure of the forest after period 1 growth and harvesting have taken place to compute the ECA of the forest at the end of period 1. Then, we use this ECA to generate the LP model for a 10 period planning horizon beginning in period 2, and solve it. Using the first period solution of this LP (corresponding to the second period of the model) we compute the ECA at the end of the second period, and use it to generate the LP for a 9 period planning horizon beginning in period 3. We repeat this process for the entire 11 period planning horizon. We construct our final solution from the first period of each of the 11 solutions. In practice, only the first period of the model solution would be implemented.

All of our models were generated using AMPL (Fourer *et al.* 1993), the mathematical programming modelling language, and solved using the Gurobi 6.0 (Gurobi, 2015) optimization solver in the order of 2 minutes using a Windows 7 workstation with an i5-3570 3.4 GHz processor and 16GB of RAM. ECA computations were carried out using ArcGIS's arcpy library, and ECA computations that were carried out at the end of each period took on the order of 30 minutes.

Harvesting strategy comparisons

We compare the *replanning framework* model solutions to the solutions generated by the *harvesting heuristic* to demonstrate that by considering the entire planning horizon, the *replanning framework* can improve upon the ECA that the *harvesting heuristic* achieved. We include ECA caribou habitat measures from the *caribou mosaic* and a *no harvesting* model for reference. We then use the *replanning framework* to assess the impact on the ECA metric, of

292 varying harvest levels, by running models that have harvest targets of 80%, 50%, and 20% of the
293 current planned harvest targets.

294 The *caribou mosaic* harvesting strategy uses a spatial zoning approach to allocate
295 harvesting in a deterministic manner over the course of the planning horizon (OMNR, 2009a).
296 Specifically, stands have been divided into eight spatially non-contiguous blocks, where each
297 stand belongs to one and only one block, which determines the period during which the stand can
298 be harvested. Some blocks are no-harvest zones (reserves), some are harvest-anytime zones and
299 others can only be harvested once during specific 20-year windows once over the course of a
300 100-year planning horizon. Following Ruppert *et al.*, (2016) we do not include constraints on the
301 timing of the harvesting of those blocks in our analysis and we do not schedule any harvesting in
302 the no-harvest blocks. Also, based on the *caribou mosaic* harvest plan, periodic harvest volumes
303 were established *a priori* using the Strategic Forest Management Model (SFMM) forest planning
304 tool (OMNR, 2007), an aspatial strategic linear programming model, and the planning horizon of
305 our model is set to 11 time periods. Each period is 10 years long except the first which is only 7
306 years long, because in 2012 we were currently 3 years into that period. Further details of the
307 *harvesting heuristic* can be found in Ruppert *et al.* (2016). To summarize, the heuristic calculates
308 a heuristic harvest value for each stand at the beginning of each planning period and schedules
309 the harvesting of stands in order of decreasing harvest value until harvest volume targets are met
310 for that period. After such harvesting, all stands develop according to yield curves defined for the
311 Trout Lake Forest (Penner *et al.* 2008), which are similar to rates of deterministic succession in
312 models used for strategic forest planning in Northwestern Ontario (OMNR 2009a).

313 Results

We compared the results obtained using our *replanning framework* LP model with the results obtained using the *harvesting heuristic*, the *caribou mosaic*, and a *no harvesting* solution. All models – with the exception of the *no harvesting* model – had the same timber harvest volume targets. The *harvesting heuristic* and the *replanning framework* required similar amounts of time to run, around 3-4 hours for the entire planning horizon, with almost all of that time dedicated to computing the ECA. We found that the *replanning framework* achieves 85% of the maximum possible forest ECA achievable over the planning horizon. The maximum possible forest ECA achievable over the planning horizon is the sum of each period's ECA obtained by running the *no harvest* model. The *replanning framework's* result compares favorably with the *harvesting heuristic* which achieves 79% of that maximum and the *caribou mosaic*, which achieves only 60% of it. The *harvesting heuristic* and the *caribou mosaic* plan were compared in Ruppert et al. (2016), so here we focus our comparison of the *replanning framework* with the *harvesting heuristic*.

Analyzing the spatial arrangement of harvests, we found that in the *replanning framework* and the *harvesting heuristic* solutions harvests have similar spatial arrangements. However, we note from our visual inspection of Figure 4, that the *replanning framework* selects harvests that are more tightly spatially clustered than the *harvesting heuristic*. This is shown by the darker, less dispersed, harvest map that results from the use of the *replanning framework*.

Examination of the patches of caribou habitat created at the end of the last period of the planning horizon reveals that both models produce similar large patches of caribou habitat (Figure 5) although the *replanning framework* creates more high quality patches (corresponding to the lightest grey in the diagram) habitat, shown more clearly in the sections from the northeast corner and western edge of the forest: panels C/D and E/F (Figure 5).

Having found that the *replanning framework* can create more caribou habitat than the *harvesting heuristic*, our next step was to assess the impact that reducing harvest volume targets might have on caribou habitat. Using the *replanning framework* for all scenarios, we found that by reducing harvest volumes after the first period by 20%, 50%, and 80% we were able to achieve 89%, 94%, and 96%, respectively, of the maximum caribou habitat (Figure 6).

Discussion

Overall there is benefit to using the *replanning framework* to prescribe harvesting decisions over the entire planning horizon. The *replanning framework* achieves more of the maximum achievable preferred caribou habitat than either the *harvesting heuristic* or the *caribou mosaic*. Further, much of this increase, particularly in comparison with the *harvesting heuristic*, is observed during the early and middle periods of the planning horizon during which there is less uncertainty concerning natural disturbance processes than later in the planning horizon. This increase is attributable to the *replanning framework* prescribing decisions over the entire planning horizon compared with the myopic *harvesting heuristic*, which prescribes them period by period. Both the *harvesting heuristic* and the *replanning framework* use the same criterion to select stands for harvest. It's therefore not surprising that the harvest maps generated by the two models look similar (Figure 4). The primary difference between them is that the harvests are more spatially clustered on the *replanning framework* map than on the *harvesting heuristic* map (Figure 4). The *replanning framework* therefore generates solutions that can be characterized by an overall reduction in the amount of habitat lost and less fragmentation of preferred caribou habitat. This results from the *replanning framework* having a smaller set of stands that it can

359 harvest without penalty than the *harvesting heuristic*, so it consistently selects the same stands
360 for harvest.

361 The final period caribou habitat maps generated by the *replanning framework* and the
362 *harvesting heuristic* also look similar (Figure 5), but we can see that the results of the differences
363 in harvesting decisions between the models in these maps. The *replanning framework* has more
364 light grey area (most preferred caribou habitat) than the *harvesting heuristic*, particularly in the
365 northeast corner of the forest (Figure 5), the top-center, and along the western edge (Figure 5),
366 reflecting areas where harvesting has not taken place for at least 6 or 7 periods. This increase in
367 the area of high quality caribou habitat is the result of having more clustered harvests when the
368 *replanning framework* is used. Not surprisingly, Figure 6 reveals that decreased harvest levels
369 increase the ECA. Further, the increase in the ECA is proportional to the decrease in harvest
370 volume and is roughly consistent from period to period. This means that if necessary, it is
371 possible to increase the amount of caribou habitat on the landscape by decreasing harvest levels,
372 though we find that substantial gains in caribou habitat require substantial reductions in harvest
373 levels.

374 We used a decreasing length planning horizon in our *replanning framework* rather than a
375 rolling planning horizon. We did so because we wanted to compare the *replanning framework*
376 and the *harvesting heuristic* for the same problem and planning horizon. Using a rolling planning
377 horizon with our *replanning framework* produces solutions that have lower ECA than the
378 decreasing length planning horizon model. In our *replanning framework* we do not use terminal
379 forest condition constraints, so nothing ensures that there is adequate timber available to harvest
380 in periods after 11 to meet future harvest targets. That is, when our *replanning framework* is
381 used, the terminal state of the forest has high ECA, but may not be in a condition such that future

harvest targets can be met, or may only be met at great cost to caribou habitat. With a rolling planning horizon model there are harvest targets for 22 periods. In order to meet harvest targets in periods after 11 it may be necessary to cut more high value caribou habitat before period 11, leading to solutions that produce less ECA in the first 11 periods than the decreasing planning horizon model. The policy and forest management planning implications of this is that there is a need to look further ahead than 100 years to accurately plan for sustainable caribou habitat.

One implication of using LP is that stands may receive partial harvest assignments (i.e., the model may schedule a particular stand to have some fraction of its area harvested according to one schedule, and the rest following one or more other schedules). In our model that optimizes a spatial attribute of the forest, the ECA, stands that are split between multiple harvest schedules could pose a problem to accurately computing individual stands' contributions to ECA. Fortunately, use of an LP model had minimal impact with respect to fractional stand harvests for two reasons.

The first is that we use a Model I (Johnson & Scheurman, 1977) LP formulation. In forest management models of large forests the majority of variables in a Model I LP model have what are known as Generalized Upper Bound (GUB) constraints (Dantzig & Van Slyke, 1967). Specifically, the variables that represent stands have GUB constraints. Dantzig and Van Slyke (1967) observed that LP models with GUB constraints have the characteristic that in an optimal solution the number of variables having a GUB constraint that can receive a partial assignment (i.e., the number of stands that can receive more than one harvest schedule) has an upper bound of the number equal to the number of non-trivial, non-GUB, constraints in the model. In our case this means that no more than 11 of 164,851 stands were split between more than one harvest schedule.

Second, we compute ECA by treating stands that are partially harvested as if the entire stand is harvested. This means that we don't overestimate the amount of caribou habitat in the forest at the cost of potentially slightly underestimating the amount of caribou habitat.

In each LP model in our replanning framework the number of harvest target constraints determined the number of stands that did receive partial harvest assignments. This begs the question, how would our *replanning framework* perform on more complicated models? The answer will depend on how complicated the models are. Our method of treating partially harvested stands as if they were completely harvested to compute caribou habitat will likely prevent modelers from overestimating the amount of caribou habitat when using the *replanning framework*. The potential underestimation of caribou habitat due to this method will depend on how complicated the LP models are.

For forests that are smaller than ours an option is to revisit IP models, and the possibility of representing caribou habitat via ECA in an integrated spatial model. We encourage researchers to investigate modelling ECA using IP. ECA could still be challenging to compute exactly within an IP model because it must take into account relationships from each stand to the rest of the stands in the forest. However, a smaller forest would make these computations substantially easier to perform than they are for the Trout Lake forest. It may also be fruitful to employ an approximation similar to the stand neighbourhoods of Öhman et al. (2011).

Several other extensions of this work are possible as well. Incorporating stand mortality, stochastic disturbances, road network construction and harvest costs into the *replanning framework* could make the model more realistic. Further, if this model were to be implemented in practice, it would be helpful to run it with a full rolling planning horizon instead of a decreasing planning horizon to produce more long term sustainability measures. It would also be

useful to investigate the inclusion of habitat patch connectivity constraints such as those in Carvajal *et al.* (2013) to the LP models so that a better approximation of the impact on forest ECA of harvesting a stand could be incorporated into the model. Forcing temporal connectivity between patches such as in Toth & McDill (2007) could be another valuable extension of our work that should be considered.

Our framework is flexible in that harvesting decisions are prescribed by incorporating replanning directly into the strategic forest management model, where harvesting decisions take into account changing forest values and consider future potential caribou habitat. This approach has been found to be more flexible than traditional optimization approaches and can more accurately capture changes in values that may occur through time, across the forest landscape (e.g., fire), marketplace (e.g., forest products) and ecological values (e.g., caribou habitat) (Gunn, 1991; Epstein *et al.* 1999; Savage *et al.*, 2010). Additionally, the framework we present could be extended to include additional economic and ecological values. For example, other boreal species are considered important to boreal forest economies, such as the American Martin (*Martes Aericana*) for trapping (OMNR, 2014). Including multiple values would require an adjustment to the harvest heuristic value calculation, which is beyond the scope of this study, but could make the *replanning framework* approach more all-encompassing by incorporating multiple economic and ecological values.

Conclusions

We have developed and used a replanning linear programming framework for maximizing caribou habitat alongside timber production. Our *replanning framework* is based on the use of a series of linear programming models that are run in sequence, where the results of each model are used to compute the ECA of the forest, which is then incorporated in the subsequent linear programming model. The *replanning framework* is an improvement over the *harvesting heuristic* presented in Ruppert *et al.* (2016) because it considers what can happen over the entire planning horizon, whereas the Ruppert *et al.* (2016) *harvesting heuristic* only prescribes decisions on a period by period basis. This allows the *replanning framework* to avoid harvesting stands that will soon become valuable caribou habitat if left undisturbed.

When we used the *replanning framework* we achieved approximately 10% more ECA in the forest than the *harvesting heuristic*, and approximately 30% more ECA than the *caribou mosaic*. We also showed that the increase in caribou habitat we could expect to achieve by decreasing harvest targets. Using the *replanning framework*, when decreasing harvests by 20%, we're able to increase the ECA by 4%, and when decreasing harvests by 80% we're able to increase ECA by 11%. Our results indicate that the largest improvements may be achieved through the spatially explicit selection of stands for harvest (by using the *replanning framework*) and not necessarily by altering the overall amount of harvest on the landscape.

In this study, we present a *replanning framework* model that improves habitat configuration (a function of habitat area and connectivity) for caribou the most, compared with other harvesting strategies, in our case study area in northwestern Ontario. However, as this planning strategy focuses on improving the configuration of old-growth forest stands, this model could also be extended to other systems where similar improvements in old growth stands are desired to achieve management goals. In summary, we find that our strategic planning approach

(*replanning framework*) can be a useful tool to help guide managers when faced with the conservation and restoration of old-growth forest stands alongside industrial timber production.

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626 **Tables**

627 **Table 1.** Classification of stands with respect to their suitability as Caribou habitat. Adapted
 628 from Ruppert et al. (2016).

Rank	Landscape Type	FRI Forest Units	Age (Years)	Description
1	Mature Jack Pine, Shallow Soils, and Rocky Outcrops	PJP, SHA, and RCK	≥ 60	Mature upland Jack Pine, shallow soil, and rocky areas
2	Treed Muskeg	TMS	-	Treed muskeg
3	Mature Conifer Mixedwood	PJM, CMX, PRW, SBM, and SBP	> 71	Mature upland conifer mixedwood and Black Spruce
4	Mature Lowland Conifer	OCL and SBL	≥ 60	Mature lowland conifer mixedwood and Black Spruce
5	Intermediate Upland Mixedwood	CMX, HMX, PJM, and SBM POA and BWD	≥ 46	Mixedwood stands of intermediate age
6	Young Conifers and Hardwoods	(along with all other conifer stands)	-	All dominant hardwood stands and younger conifer stands
7	Water and Wetlands	WAT and OMS	-	Lakes, Rivers, and marsh areas
8	Recent Disturbance	All merchantable wood units	< 20	Recently disturbed areas (e.g., harvest, fire)
9	Linear Features	-	-	Current road and utility line infrastructure

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Figure Labels

Figure 1. The Trout Lake Forest Management Unit (FMU) with woodland caribou distribution (light grey) and all FMUs (dark grey outline). Woodland caribou range data is from OMNR (2010) and FMU data from OMNR (2006). Adapted from Ruppert et al. (2016).

Figure 2. Schematic diagram of the *replanning framework*.

Figure 3. ECA levels for all of the planning models over an 11 period planning horizon. This includes the *harvesting heuristic*, the *caribou mosaic*, the *replanning framework*, and the *no harvest* models.

Figure 4. Allocated harvest over the entire planning horizon (11 planning periods; 107 years) for the Trout Lake forest for (A,B) the entire spatial extent and (C,D) a section from the southwestern corner. Shown are solutions using (A,C) the *replanning framework* and (B,D) the *harvesting heuristic*. Dark areas indicate planned harvests.

Figure 5. The assigned caribou habitat value on the terminal landscape under the (A,C,E) *replanning framework* and (B,D,F) *harvesting heuristic*. Shown is the (A,B) entire spatial extent of the Trout Lake forest, (C,D) a section from the northeast corner, and (E,F) a section from the western edge. Lighter colours on the map indicate higher quality caribou habitat given by the ECA metric.

Figure 6. The overall (A) ECA for each of the harvest scenario during the first 5 planning periods and the (B) ECA for each of the harvest scenarios during the last 6 periods

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Figures

Figure 1.

679 **Figure 2.**

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Figure 3.

681 **Figure 4.**

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683 **Figure 5.**

Figure 6.

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Rank	Landscape Type	FRI Forest Units
1	Mature Jack Pine, Shallow Soils, and Rocky Outcrops	PJP, SHA, RCK
2	Treed Muskeg	TMS
3	Mature Conifer Mixedwood	PJM, CMX, PRW, SBM, SBP
4	Mature Lowland Conifer	OCL, SBL
5	Intermediate Upland Mixedwood	CMX, HMX, PJM, SBM
6	Young Conifers and Hardwoods	POA, BWD, all other conifer stands
7	Water and Wetlands	WAT, OMS
8	Recent Disturbances	All merchantable wood units
9	Linear Features	--

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Age (Years)	Description
>= 60	Mature upland Jack Pine, shallow soil and rocky areas
--	Treed muskeg
> 71	Mature upland conifer mixedwood and Black Spruce
>= 60	Mature lowland conifer mixedwood and Black Spruce
>= 46	Mixedwood stands of intermediate age
--	All dominant hardwood stands and younger conifer stands
--	Lakes, Rivers, and marsh areas
< 20	Recently disturbed areas (e.g. harvest, fire)
--	Current road and utility line infrastructure

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