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**Conserving woodland caribou habitat while maintaining
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Title: Conserving woodland caribou habitat while maintaining timber yield: A graph theory approach

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Abstract

The fragmentation and loss of old-growth forest has led to the decline of many forest dwelling species that depend on old-growth forest as habitat. Emblematic of this issue in many areas of the managed boreal forest in Canada, is the threatened woodland caribou (*Rangifer tarandus caribou*). We develop a methodology to help determine when and how timber can be harvested in order to best satisfy both industrial timber supply and woodland caribou habitat requirements. To start, we use least-cost paths based on graph theory, to determine the configuration of woodland caribou preferred habitat patches. We then developed a heuristic procedure to schedule timber harvesting based on a trade-off between merchantable wood volume and the remaining amount of habitat and its connectivity during a planning cycle. Our heuristic can attain 84% of the potential woodland caribou habitat that would be available in the absence of harvesting, at the end of a 100-year planning horizon. Interestingly, this is more than the current plan (50%) and a harvesting plan that targets high volume stands (32%). Our results indicate that our heuristic procedure (i.e., an ecologically-tuned optimization approach) may better direct industrial activities to improve old growth habitat while maintaining specified timber production levels.

Keywords (3-5): economic values, ecological values, graph theory, least-cost paths, habitat configuration

52 Introduction

53 Globally, industrial forest management practices have directly contributed to the widespread
54 fragmentation and loss of old-growth forests (Lindenmayer et al. 2012). Industrial management
55 practices can also, for example, modify the frequency and severity of several different types of
56 forest disturbances that contribute to the fragmentation and loss of old-growth forest stands,
57 including: timber harvesting, wildfire, insect outbreaks and land use change (Butchart et al.
58 2010; Brandt et al. 2013). As a consequence, declines in biodiversity tend to be related to many
59 of these modified forest landscapes (Butchart et al. 2010; Burivalova et al. 2014; Venier et al.
60 2014). For the forest-dwelling woodland caribou (*Rangifer tarandus caribou*), the fragmentation
61 and loss of preferred old-growth conifer forest, has contributed to population declines and range
62 recession within North America (Bergerud 1974; Schaefer 2003; Vors et al. 2007). Currently, the
63 majority of this range recession is occurring alongside areas of land use change and industrial
64 timber production in the boreal forest region, where the area disturbed by harvesting activity in
65 these managed regions can now well exceed the area disturbed due to natural disturbances
66 (Brandt et al. 2013; Venier et al. 2014). As a result, reviews by the Committee on the Status of
67 Endangered Wildlife in Canada (COSEWIC) have led to the listing of woodland caribou as a
68 threatened species throughout many regions (COSEWIC 2000; COSSARO 2005).

69 Woodland caribou, like many other species, evolved alongside natural boreal forest
70 disturbances (e.g., forest fires) that have an impact on spatio-temporal patterns of their preferred
71 habitat. However, within the managed regions of the Canadian boreal, fire suppression activities
72 have altered fire disturbance patterns by producing a greater number of small fires and increasing
73 the mean fire return interval (Martell & Sun 2008; Venier et al. 2014). This change in fire
74 disturbance, within the managed regions, may provide woodland caribou with more habitat, by

reducing the amount of area impacted by fire, but at the same time the added pressures of timber harvesting, linear features and other changes in land use (e.g., transportation networks, utility corridors) have become the major contributors to increased fragmentation and habitat loss (Environment Canada 2011; Venier et al. 2014). Woodland caribou are affected by fragmentation and habitat loss through decreases in resource availability, primarily terrestrial lichen understorey, through the avoidance of roads (i.e., traffic), and by increases in predator populations (Wittmer et al. 2005; Vors et al. 2007; Thompson et al. 2015). Forest disturbances reduce lichen availability, which can contribute to poor body condition and reduced calf survival rates (Parker et al. 2005; Thompson et al. 2015). Additionally, forest disturbances contribute to increases in the amount of early seral boreal forest. This increases suitable forage for white-tailed deer (*Odocoileus virginianus*) and moose (*Alces alces andersoni*) populations (Wittmer et al. 2005). Subsequent increases in the abundance of deer and moose populations, desirable prey species for black bears (*Ursus americanus*) and wolves (*Canis lupus*), have led to increases in predator populations that will opportunistically prey upon woodland caribou thereby increasing their predation pressure (Wittmer et al. 2005). Thus, harvesting activities that fragment and reduce the amount of preferred habitat, are believed to be a major contributor to woodland caribou declines by altering resource availability and increasing predation pressure.

To achieve long-term sustainability of forested landscapes, managers are required to develop sustainable forest management plans that achieve an appropriate balance of multiple economic, ecological, and social objectives (Gunn 2007; Adams 2014). Management of industrial wood supply in Ontario provides a good study system, as there is conflict between the southern range limit of woodland caribou and northern limit of timber production for industry within the province (Figure 1). Further, there is already a harvesting strategy that is designed to mitigate the

impacts of timber harvesting on woodland caribou habitat, termed the Dynamic Caribou Habitat Schedule (DCHS; hereafter referred to as the *caribou mosaic*), which has been in place for the last 10-15 years depending on the specific location (Racey et al. 1999; OMNR 2014). One limitation to this strategy is its deterministic design wherein the spatial arrangement of cut blocks, which includes the area, position and perimeter of areas available for harvesting, are specified for an entire 100+ year planning horizon at the start of that planning horizon. Using a deterministic design such as this may be problematic when considering how dynamic a forested ecosystem can be over century long time periods due to the possible but uncertain potential changes to the forest landscape (e.g., forest stand composition, habitat conditions), marketplace (e.g., value of timber, forest products), or social values (e.g. management objectives; Rayfield et al. 2008; Savage et al. 2010). This is one reason why, long-term harvest schedules generated by planning models are not implemented beyond the first planning cycle (e.g., 10 years for the *caribou mosaic*). Periodically (e.g., every 5 or 10 years) a new plan is usually developed to allow managers to adapt their plans to changing conditions (called replanning) when the current plan becomes infeasible or suboptimal for industry and/or woodland caribou needs (Gunn 1991; Martell et al. 1998; Baskent & Keles 2005). Current harvest strategies are developed with replanning in mind and since replanning is not directly incorporated into its framework, it may not reflect well, what changes might actually take place on the forest landscape, in the marketplace, or on ecological values over the long-term.

A second limitation is that there is currently a management focus on maintaining or increasing preferred habitat area by reducing the cumulative area of disturbance to woodland caribou across the landscape (OMNR 2009a ; Environment Canada 2011). However, as is the case with many other species, woodland caribou move through the landscape on an annual basis

and will demonstrate some site fidelity from year-to-year (i.e., they will tend to use the same areas from year-to-year; Ferguson & Elkie 2004). On the other hand, there are some seasons during which such site fidelity does not appear to hold very well (e.g., winter grounds can change location by 6-15 km year-to-year; Ferguson & Elkie 2004). This implies that considering the configuration of preferred habitat, a combination of connectivity and area, may be a good approach when the use of particular habitat patches can be quite variable year-to-year in the effort for woodland caribou to gain access to resources and to avoid predation (O'Brien et al. 2006; Mayor et al. 2007; Hins et al. 2009). In other words, providing habitat is necessary to achieve conservation goals, but if habitat is highly fragmented, it may not be sufficient due to the movement patterns and constraints of the species of concern (Fahrig 1998; Fahrig 2003; Baskett & Keles 2005; Hanski 2005). This potential shortcoming indicates that explicitly incorporating the configuration of preferred habitat into management plans may be crucial, especially if industrial timber production activities can potentially worsen preferred habitat configuration for woodland caribou.

In our study, we address these simplifying assumptions (no replanning and no explicit consideration of the spatial arrangement of habitat) by developing a harvesting strategy that is assessed in terms of the economic values for industry and habitat values for woodland caribou within each forest stand during each planning period. We begin by determining the value of a forest stand based on woodland caribou habitat preferences and the spatial configuration of preferred habitat patches (area and connectivity) within the landscape to facilitate woodland caribou movement in the managed forested landscape. We then formulate and use a harvest scheduling heuristic that selects forest stands for harvest based on the volume of merchantable timber in the stand and the woodland caribou habitat value of a forest stand during each period of

the planning horizon. Finally, we evaluate four harvesting strategies (including the current *caribou mosaic* plan and our *harvesting heuristic*) to investigate long-term trade-offs of wood supply and woodland caribou conservation.

Methods

Study Area and Data

Our study area is the Trout Lake forest located in northwestern Ontario (Figure 1). The Trout Lake forest is an area of approximately one million hectares within the boreal forest region of Canada. It is an area of active timber production and provides habitat for woodland caribou (Figure 1; OMNR 2009a; Environment Canada 2011). We used Forest Resource Inventory (FRI) data updated to 2012 (provided by the Ontario Ministry of Natural Resources and Forests) to classify woodland caribou habitat and evaluate forest harvesting strategies (OMNR 2009b). We first created forest planning units that are 62,500 m² (or 6.25 ha) in size and classified them as being either a type of forest (designated as one of twelve forest types to be managed using one of four silviculture strategies) or a non-forest unit (e.g., water, wetland, treed muskeg; see OMNR 2009b for more details). As of 2012, we found that the age class distribution of forest stands in the Trout Lake forest is multimodal with peaks at 0-20, 40-60 and 90-110 years (Figure S1A), which is a result of recent timber harvesting activities (< 20 years) and the legacy of large natural disturbances such as fire (OMNR 2009a). The Trout Lake forest is dominated by coniferous canopy species, black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*), which make up >80% of the forest canopy (Figure S1B).

Forest management plans in northwestern Ontario are developed using a hierarchical design process where, at the highest level, wood production is constrained by what is termed the

Dynamic Caribou Habitat Schedule (DCHS). Briefly, the DCHS constrains wood production temporally across tracts of land over a 100-year block rotation (Racey et al. 1999; OMNR 2014). The Trout Lake forest was partitioned into seven zones that are subject to the following temporal harvest constraints: reserve zones (no harvesting), harvesting anytime (0-100 years), and harvesting to occur in block A (0-20 years), block B (21-40 years), block C (41-60 years), block D (61-80 years), and block E (81-100 years; Figure S2). Finally, since the first 13 years of this plan for the Trout Lake forest was implemented beginning in year 2012, we start our analysis with the last 7 years in the A blocks (Figure S2A), before moving in sequential order through blocks B, C, D, and E. For simplicity, we refer to this remaining 7 years as the first 10 years of all harvesting strategies within this study.

Long-term harvesting and silviculture plans are derived from the current management plan, where harvest scheduling has been determined using the Strategic Forest Management Model (SFMM; OMNR 2009a). SFMM (a variant of Model III) is not a spatially explicit planning model that can incorporate both deterministic and stochastic processes through the use of deterministic mean rates of succession and natural disturbance processes (Boychuk & Martell 1996; OMNR 2007). In this instance, the spatial aspect of harvest planning is implemented in SFMM by using regional constraints (or zones) that specify when harvesting can take place in each zone (Figure S2). We use annual target volumes outlined in the current plan for the Trout Lake forest, ranging between 670,000 - 865,000 m³ per annum, when harvest occurs in any of our strategies (OMNR 2009a).

Economic timber and caribou habitat value of a forest stand

We consider two different values of a forest; the economic value of the timber and the woodland caribou conservation value, both of which are incorporated into our heuristic (see Figure 2 for

details). The economic value of the timber is based on the volume of merchantable wood in a forest stand. To estimate the volume of a given forest stand we used yield curves currently defined and used in strategic forest management strategies for the Trout Lake forest management unit (Penner et al. 2008; OMNR 2009a).

The woodland caribou conservation value of a forest stand was determined by first classifying the FRI data (or forest planning units) based primarily on winter habitat preferences, which generally reflect the habitat requirements of woodland caribou throughout the year (O'Brien et al. 2006; Environment Canada 2011; McGreer et al. 2015). Winter habitat use occurs during a critical period for woodland caribou, where they face decreased availability of resources and harsh weather, which can have a dramatic impact on survival (Parker et al. 2005). Here we define the most preferred habitat type for woodland caribou as mature jack pine stands (jack pine stands with an age of greater than 60 years), rocky outcrops, and shallow soil sites, which likely sustain high levels of terrestrial lichen understory (a preferred resource for woodland caribou; Table 1 and Figure 3A). In contrast, recently (< 20 years) disturbed areas (cutovers or burns) and linear features (roads and utility corridors) are the least desired landscape features for woodland caribou (Table 1 and Figure 3A). We also used 500 m buffers of influence for edge effects of disturbances that negatively impact woodland caribou (i.e., recently disturbed areas (age < 20 years) and linear features, such as roads and utility corridors; Environment Canada 2011). Linear features, such as roads and utility corridors, were obtained from Ontario Base Maps and included both current road infrastructure and utility corridors throughout the Trout Lake forest (OMNR 2003). As we are primarily interested in assessing the impact of harvest schedule plans (i.e., the placement and area of harvest), we only included the current configuration of roads and utility corridors. For the purpose of this research, we did not model for future road creation and

decommissioning that may take place in the Trout Lake forest. Calving habitats, which are critical to successful woodland caribou reproduction (e.g., small islands, peninsulas and muskeg) were accounted for by being present in reserves as well as by being classified as highly suitable habitats (Table 1). Here we refer to a caribou habitat patch as the most preferred habitat type (Table 1), where the smallest sized patch is a single forest stand (6.25 ha). Habitat classifications were conducted using both Python v2.7.8 and ArcGIS 10.2 software.

After ranking habitat preferences of each stand we created a cost surface for woodland caribou that reflects their habitat use and movement within the Canadian Shield region of the boreal forest in northwestern Ontario (Table 1). Using this cost surface we then use a graph theoretical approach with preferred habitat as nodes (where adjoining preferred habitat stands are merged) and least-cost paths as arcs delineating potential direct movement between patches (Adriaensen et al. 2003; Fall et al. 2007). Least-cost paths represent potential movement paths for which no other path between two habitat patches has a lower cost (i.e., lowest cost given the distance travelled and avoidance of highly unsuitable or “costly” habitat; see Adriaensen et al. 2003 and Fall et al. 2007 for more details). This routine was implemented using the R software *grainscape* package that invokes the Spatially Explicit Landscape Event Simulator (SELES) algorithm to implement least-cost path routines (Fall et al. 2007; Galpern et al. 2012).

To determine the value of a habitat patch relative to all the other habitat patches in the landscape, we first determine the overall landscape value and calculate the marginal contribution of a habitat patch to the overall landscape using the Equivalent Connected Area (ECA) metric (Eq. 1):

$$ECA = \sqrt{\sum_{i=1}^n \sum_{j=1}^n a_i a_j p_{ij}} \quad (1)$$

235 where, a_i is the area of habitat patch i , a_j is the area of patch j , p_{ij} is the maximum product
236 probability of movement between patch i and j , and n is the total number of patches on the
237 landscape (Saura et al. 2011). The probability of direct dispersal (i.e., the probability that a
238 woodland caribou will move to a patch without using other patches) between all patches is
239 calculated using a negative exponential dispersal kernel, which is defined by an alpha parameter
240 ($\alpha=0.5$) and the length of a least-cost link (d) between patches ($\log(\alpha)/d$; Urban & Keitt 2001;
241 Saura et al. 2011). The maximum product probability (p_{ij}) is then calculated as the maximum
242 probability of movement using all potential paths between patches i and j , including paths that
243 utilize other patches (Figure S3; see supplementary for details). Throughout this study we only
244 present one solution for simplicity and use a median dispersal distance of 40 km, which provides
245 the largest improvement in overall habitat area on the Trout Lake forest landscape (Figure S4)
246 and represents a balance between a range of movements representing approximate daily (1 km)
247 and annual (80 km) movement distances for woodland caribou within the region (Ferguson &
248 Elkie 2004). Then to assess each harvesting strategy, we perform a sensitivity analysis of the
249 ECA landscape metric using five different median dispersal distances (1, 10, 25, 40, 80 km).
250 Lastly, to calculate the marginal value of each patch we perform a take-one-out procedure to
251 calculate the contribution of each patch to the overall landscape ECA value. This procedure is
252 conducted in R software using packages *igraph* and *raster* within this routine (R Development
253 Core Team 2015).

254 *Harvesting heuristic*

255 We designed a harvesting heuristic to maximize ECA during each planning period by selecting
256 for harvest, stands that have large wood volumes, but that are located away from high value
257 woodland caribou habitat patches (Eq. 2). Specifically, the heuristic harvest value is 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. Forest stands are scheduled to be harvested in each planning period such that the highest heuristic harvest value stands (H_i) are targeted first until wood volume constraints are met (Figure 2), where the harvest value is:

$$H_i = b (V_i) - c \left(\frac{ECA_i}{(1+D_i)} \right) \quad (2)$$

Here, the heuristic harvest value (H_i) of a stand includes the parameters b and c , V_i is the total volume of merchantable wood in the stand (m^3), ECA_i is the marginal equivalent connected area value of the nearest habitat patch (hectares), and D_i is the distance to the nearest woodland caribou habitat patch (metres). The parameters allow the heuristic to be tuned to achieve a range of objectives. Setting $b > c$ would put more emphasis on harvesting high volume stands, whereas setting $b < c$ would emphasize harvesting stands further away from caribou habitat (see Figure S5). For the purposes of this study we set values for parameters at $b = c = 1$, which produced the harvest values for each forest stand on the initial landscape in the Trout Lake forest shown in Figure 3B.

Harvest scheduling comparisons

We then used deterministic succession rules (stands age, but do not change types through time) with no fire on our landscape, to assess the utility and impact of using this heuristic. Although succession is admittedly not a purely deterministic process, current strategic forest management models (SFMM) use successional processes in a deterministic fashion (OMNR 2009a). Further, we are interested in assessing how harvesting strategies may work in relation to habitat configuration and have opted to not evaluate these alongside the added complexity of stochastic processes (e.g., fire, succession, insect outbreaks) at this stage. We evaluated four harvest

strategies for comparison; (1) *no harvesting*, (2) *relaxed caribou mosaic* (no regional spatial constraints, except no harvesting in designated reserves), (3) *caribou mosaic* (the current cut block rotation applied to the Trout Lake forest; DCHS), and (4) our *harvesting heuristic*. For the *caribou mosaic* strategy, regional spatial constraints are present (Figure S2), whereas the *relaxed caribou mosaic* strategy does not have any regional spatial constraints, except for precluding harvesting within reserves. With the *relaxed caribou mosaic* and *caribou mosaic* strategies, when harvest constraints are met, forest stands with higher volumes of wood are always selected in decreasing order from highest to lowest. For the *harvesting heuristic*, harvesting occurs in order of harvest value (Eq. 2), where higher values are targeted first (reserves are not included in the harvest allocation; Figure 2). Harvest allocation continues with all strategies until timber production volume targets have been satisfied for each planning period. All harvesting strategies and routines were developed using Python v2.7.8 and ArcGIS 10.2 software.

To assess differences between harvesting strategies we needed to evaluate how the landscape is predicted to change over the course of the planning horizon with respect to woodland caribou habitat. Since the ECA metric is our objective function in the *harvesting heuristic* strategy we first assess how the ECA of each harvesting strategy changes through time using five different median dispersal distances (1, 10, 25, 40, and 80 km). However, because using the ECA may be viewed as being circular (i.e., using the ECA to evaluate its own performance or metrics similar to ECA (e.g., overall area)), we partitioned the landscape into one portion that was harvested (at least once) and another portion that is never harvested over the course of the 100-year planning horizon. We then assessed how the number of patches and the amount of preferred woodland caribou habitat differed within harvested and non-harvested areas on the landscape for each strategy.

Results

Comparing the overall habitat configuration

The four strategies we evaluated produced quite different woodland caribou habitat area and connectivity trajectories over the planning horizon (Figure 4). As expected, under a strategy with *no harvesting*, the (i.e., the average across different dispersal distances of 1, 10, 25, 40, and 80 km) landscape area and connectivity of woodland caribou habitat would improve the most over time (Figure 4A and 4B). With timber harvesting, our *harvesting heuristic* provides the highest improvement and maintenance of habitat area and connectivity for woodland caribou over the course of the planning horizon (Figure 4A and 4C). Interestingly, the current *caribou mosaic* strategy in Ontario provides an initial improvement over the first 30 years of the planning horizon (Figure 4A and 4D), but after that point in time it exhibits a declining value of woodland caribou habitat area and connectivity. Finally, not surprisingly the *relaxed caribou mosaic* strategy consistently performs the worst with respect to improving and maintaining woodland caribou habitat area and connectivity across the landscape (with the exception of the 80 year time period; Figure 4A and 4E). In fact, over the long-term (>60 years), the *relaxed caribou mosaic* strategy has a woodland caribou habitat area and connectivity across the landscape that is similar to the current *caribou mosaic* strategy (Figure 4A), where both strategies are almost consistently well below the *no harvesting* strategy. Finally, reductions in harvest levels (by comparing the *no harvesting* to other harvest strategies) would not lead to large changes in ECA for the *harvesting heuristic* compared to other strategies (Figure 4A).

The four strategies evaluated produce different woodland caribou habitat area and connectivity trajectories over the planning horizon (Figure 5). As expected, under the *no harvesting* strategy, preferred habitat area and number of patches would improve the most over

time in areas that are not harvested (Figure 5A and 5C). Within areas that are harvested at least once, we find that the *caribou mosaic* strategy allocates the most preferred habitat in area and number of patches (Figure 5B and 5D) compared to any other strategy. With timber harvesting, we find that our *harvesting heuristic* provides the highest improvement and maintenance of habitat area and number of patches for woodland caribou within non-harvested areas over the planning horizon (Figure 5A and 5C).

Spatial configuration of woodland caribou habitat and timber harvest

The spatial configuration of woodland caribou habitat is different when comparing the 100-year old simulated landscapes under the four harvesting strategies (Figure 6). The *no harvesting* strategy provides the largest number of patches, links and habitat area across the Trout Lake forest (Figure 6A and Table 2). When we consider timber harvesting, the *harvesting heuristic* supplies more habitat than the other harvest strategies considered, but the number of habitat patches and links represents only the third highest of all of the strategies (Figure 6B and Table 2). It achieves this by creating larger habitat patches and creates large tracts of habitat patches in the southeast and to a lesser extent, the northwest region of the Trout Lake forest. In contrast, the *caribou mosaic* strategy produces a larger number of habitat patches and links, although less overall habitat area in comparison to the *harvesting heuristic*, meaning the habitat patch size is much smaller than that found with the *harvesting heuristic* (Figure 6C and Table 2). While the *caribou mosaic* strategy produces some areas that contain a large amount of habitat and connectivity, these are less substantial in size in comparison to the *harvesting heuristic*. Finally, we find the *relaxed caribou mosaic* strategy produces the least number of patches, the least number of links and the least amount of habitat compared to other strategies (Figure 6D and

Table 2). The *relaxed caribou mosaic* strategy produces habitat areas that appear to be smaller in size and widely dispersed.

The resulting configuration of habitat patches and links mirrors that of stands that are selected for harvest over the course of the planning horizon (Figures 6 and 7). The *harvesting heuristic* concentrates harvesting activities spatially, creating areas in the southeast and to a lesser extent in the northwest, where harvesting does not occur (Figure 7A). The *caribou mosaic* and *relaxed caribou mosaic* strategies appear similar in their selection of forest stands over the course of the planning horizon (Figure 7B, 7C). However, where the selection of stands for harvest occurred twice over the planning horizon, the *caribou mosaic* concentrates these second harvests within the anytime block (Figure S2F, 7B) and the *relaxed caribou mosaic* strategy distributes these second harvests throughout the Trout Lake forest (Figure 7C).

Aspatial assessments of woodland caribou habitat

When considering current anthropogenic linear features (e.g., roads and utility corridors) and recent (< 20 years) forest disturbances with potential edge effects of 500 m, the overall amount of habitat disturbed under the four strategies does not differ dramatically over the course of the 100-year planning horizon (Figure 8). We find that the legacy of harvesting and fire within the Trout Lake forest represents a substantial amount of disturbance for woodland caribou over the first 20 years of the planning horizon (Figure 8). As we had expected, the least amount of disturbance across the landscape occurs under the no harvesting strategy (Figure 8). In contrast, the other three harvesting strategies vary within a range of 23-39% disturbance to woodland caribou within the Trout Lake forest after the first 20 years of the planning horizon (Figure 8). Specifically, after the first 20 years the lowest disturbance values are found with the *caribou mosaic* strategy (23-35%), followed by the *relaxed caribou mosaic* (33-38%) and the *harvesting*

heuristic (33-39%; Figure 8). These values are either within a range that is considered suitable levels of disturbance (<35%) or are within a lower range values of disturbance levels that are considered to be uncertain if woodland caribou may be able to tolerate (35-45%; Environment Canada 2011).

Discussion

Sustainable forest management plans call for an appropriate balance of multiple objectives. When balancing woodland caribou conservation and industrial economic values, we find that the *harvesting heuristic* performed better than the other three timber harvesting strategies we considered (Figures 4 and 5). The *harvesting heuristic* produces more area and a better spatial configuration of habitat for woodland caribou across the landscape compared with the other strategies that schedule timber harvesting to meet industrial needs. Specifically, the *harvesting heuristic* strategy maintained 84% of the potential woodland caribou habitat (compared with 50% and 32% for the *caribou mosaic* and *relaxed caribou mosaic* strategies, respectively; Figure 4A) on the landscape compared to the amount that could result under conditions with *no harvesting* at the end of the 100-year planning horizon (Table 2). Interestingly, we found that while the *caribou mosaic* and *relaxed caribou mosaic* harvesting strategies produce similar levels of preferred habitat within non-harvested areas, the *caribou mosaic* provides slightly more preferred habitat by allocating it within areas that will be harvested or have been harvested (Figure 5A). The *harvesting heuristic* is able to achieve an improvement in levels of habitat configuration and area by allocating most of the harvest away from high value woodland caribou patches (Equation 2 and Figure 7A). In doing so, this *harvesting heuristic* concentrates anthropogenic activities, which has been demonstrated to be a strategy that may better achieve conservation goals for improving and maintaining levels of old growth boreal forest (a desirable

habitat type for woodland caribou; Tittler et al. 2012; Bouchard & Garet 2014). Further, concentrating timber harvesting may have an added economic benefit by reducing the amount of roads that need to be built and maintained to access stands for timber production. For these reasons, it appears that the *harvesting heuristic* strategy may be able to strike a better balance between our two objectives, economic and conservation values, over the course of the planning horizon by producing larger habitat patches with more connectivity, while satisfying current annual wood supply levels.

Incorporating habitat configuration into forest management planning

Habitat guidelines specify that woodland caribou require approximately 65% of the landscape to not be disturbed by natural and anthropogenic activities (e.g., roads, timber harvesting, fire) with an uncertain result within a range of 55-65% (Environment Canada 2011). We have demonstrated that under scenarios that do not account for natural disturbances (e.g., fire, insect outbreaks) and focus only on recent known disturbances (<20 years), that this threshold may be met, albeit after an initial 20 year period when the lag effects of recent large scale fires have receded (Figure 8). However, given the relatively short fire return interval for northwestern Ontario (~84 years; Boulanger et al. 2012), we may expect that fire on the landscape and the inclusion of future road building may make this 65% threshold and potentially the 55% threshold unattainable not only for the Trout Lake forest, but other FMUs within the region.

Regardless of whether a percentage disturbance target is attainable alongside projected levels of harvesting activities, it is important to highlight that the overall measure of percent disturbance across the landscape is an aspatial metric. All three timber harvesting strategies evaluated in this study have different spatial habitat configurations, but more similar rates of percent disturbance throughout the planning horizon (Figures 6 and 8). Spatial habitat

configuration has an impact on the ability of species to acquire resources and avoid predation and it can also impact landscape scale processes that includes metapopulation dynamics (exchange of individuals between populations in terms of immigration and emigration; Hanski 2005). For woodland caribou in particular, previous studies indicate that habitat configuration is important (O'Brien et al. 2006; Mayor et al. 2007; Hins et al. 2009) as is the impact of edge effects of disturbed and developed (e.g., roads) areas (Vors et al. 2007). Further, habitat configuration will also likely play a more important role when habitat becomes more limited across the landscape (Fahrig 1998), which appears to be the case for many woodland caribou populations within the managed portion of the boreal forest region in Canada (Environment Canada 2011), and that may be the case for many other forest dwelling species (Butchart et al. 2010; Burivalova et al. 2014). Thus, at the very least, integrating habitat configuration into forest management planning, as is done *a priori* with the *caribou mosaic* strategy (with large spatial zoning) or by allowing more flexibility as shown with the *harvesting heuristic* strategy, may provide some ways of allowing for higher levels of timber harvesting while also improving and maintaining woodland caribou habitat across the landscape.

Limitations and future directions

There are several limitations of our methodology, which if addressed, could improve our ability to achieve a better balance between timber production and woodland caribou conservation objectives. Firstly, FMUs in Ontario, while millions of hectares in size and subject to same guidelines, stakeholder input, and decision processes, are developed largely independently of each other (OMNR 2014). This can be problematic given that the size of the ranges of local populations of woodland caribou in northern Ontario, which can encompass 3-5 different FMUs. This means one herd would require habitat that is appropriately distributed across several FMUs,

which is not currently accounted for when forest management plans are developed and implemented at the single FMU level. This begs the question whether forest management plans are at the appropriate spatial scale for woodland caribou conservation and it appears that the management of woodland caribou may require a broader spatial scale of management. Secondly, a critical knowledge gap remains as we understand that habitat configuration is important for woodland caribou (O'Brien et al. 2006; Mayor et al. 2007; Hins et al. 2009), but we do not have a clear understanding of what level of habitat configuration (i.e., equivalent connected area) is required for woodland caribou persistence. A better understanding of habitat configuration and its impact on local population level dynamics (e.g., recruitment) for woodland caribou will undoubtedly better inform both models and forest management practices.

There is also a need to develop a spatial landscape optimization model that can be used to evaluate and potentially improve upon our heuristic (Ohman 2000; Williams et al. 2004; Gunn 2007; Carvajal et al. 2015). From an economic perspective, an optimization approach will likely improve stand selection for harvest by incorporating costs alongside revenues, which may result in an altered harvest allocation that could potentially impact woodland caribou habitat differently across the landscape. Secondly, incorporating stochastic processes, such as uncertain fire and forest succession in the boreal forest, should be investigated to determine how uncertainty may impact our ability to achieve the similar outcomes (Boyчук & Martell 1996; Savage et al. 2010). As was suggested in the previous section, including stochastic processes in our methodology would increase disturbance for woodland caribou and would also impact the resulting habitat configuration. This may also highlight other details with the *harvesting heuristic* strategy, where the selection of stands for harvest can better respond to changing landscape values that may result from uncertain disturbances (e.g., large scale fires). Finally, there is

currently little information on how road networks are constructed (Pulkki 2003), let alone decommissioned, to accurately account for future road building. Regardless, an algorithm based on some simple rules (e.g., roads are not built over water if it can be avoided) could be developed to provide some insight into how future road building alongside timber harvesting may impact woodland caribou.

Conclusions

Our *harvesting heuristic*, which is designed to trade-off economic and ecological objectives, produces solutions that will help assess woodland caribou habitat provisioning in the face of fixed timber supply. We demonstrate that by avoiding high woodland caribou value stands one can help offset the detrimental impacts of timber harvesting activities and meet industrial timber supply needs. Further, our *harvesting heuristic* constitutes a flexible approach to forecasting long-term timber production as it is implemented between planning periods, as opposed to a deterministic design that follows a set strategy over the entire planning horizon. This has a two-fold benefit, economically and ecologically, of responding to changes in values over time, which may lead to more realistic outcomes when assessing long-term impacts of planning decisions. We incorporate spatial considerations in our planning method for woodland caribou conservation, providing harvest scheduling outcomes that have higher levels of habitat area and connectivity between patches. Our results also suggest that if we consider stochastic processes alongside harvesting activities, harvesting rates may need to be reduced if current defined thresholds (e.g., percent disturbance) are used as management guidelines. However, these aspatial guidelines are limited in application and further understanding is required to reduce uncertainty surrounding the spatial constraints of woodland caribou populations. Lastly, the *harvesting heuristic* strategy framework is also flexible in that it can be easily adapted to

incorporate other forest values, such as Marten (*Martes americana*) habitat or habitat preferences of other species of interest. In summary, our model suggests that incorporating our current knowledge of species habitat requirements, both habitat preference and its spatial configuration, into timber harvest models will lead to more desirable outcomes for conservation while meeting the economic needs of industry within the boreal forest ecosystem.

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631 **Tables**

632 **Table 1.** Description of woodland caribou habitat classifications using Forest Resource Inventory (FRI) data. Listed is the rank of
633 preference, landscape type, FRI forest units, age, description and the associated cost used within the cost surface. These ranks and
634 values were derived from O’Brien *et al.* (2006) and the Environment Canada (2011) critical habitat assessment.

Rank	Landscape Type	FRI Forest Units	Age (Years)	Description	Cost
1	Mature Jack Pine, Shallow Soils, and Rocky Outcrops	PJP, SHA, and RCK	≥ 60	Mature upland Jack Pine, shallow soil, and rocky areas	1
2	Treed Muskeg	TMS	-	Treed muskeg	1.1
3	Mature Conifer Mixedwood	PJM, CMX, PRW, SBM, and SBP	> 71	Mature upland conifer mixedwood and Black Spruce	1.75
4	Mature Lowland Conifer	OCL and SBL	≥ 60	Mature lowland conifer mixedwood and Black Spruce	1.75
5	Intermediate Upland Mixedwood	CMX, HMX, PJM, and SBM	≥ 46	Mixedwood stands of intermediate age	2
6	Young Conifers and Hardwoods	POA and BWD (along with all other conifer stands)	-	All dominant hardwood stands and younger conifer stands	2
7	Water and Wetlands	WAT and OMS	-	Lakes, Rivers, and marsh areas	3.5
8	Recent Disturbance	All merchantable wood units	< 20	Recently disturbed areas (e.g., harvest, fire)	5
9	Linear Features	-	-	Current road and utility line infrastructure	10

Table 2. Summary statistics for the final landscape at the end of the 100 year planning horizon using a median dispersal distance of 40 km. Shown is the number of woodland caribou habitat patches, number of links, total preferred habitat area, and the overall landscape Equivalent Connected Area (ECA; a measure of woodland caribou habitat connectivity and area).

Strategy	Number of Patches	Number of Links	Habitat Amount (ha)	ECA (ha)
No Harvest	1,543	3,955	121,643.8	90,228.5
Heuristic	1,027	2,650	95,856.3	75,370.6
Mosaic	1,194	3,123	68,612.5	45,257.2
Relaxed	832	2,198	44,593.8	28,929.5

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Figure Legends

Figure 1. The study area, Trout Lake Forest Management Unit (FMU), with respect to woodland caribou distribution (light grey) and all FMUs (dark grey outline) in the province of Ontario. Woodland caribou range data is from OMNR (2010) and FMU data from OMNR (2006).

Figure 2. A schematic diagram of the harvesting heuristic.

Figure 3. (A) The initial habitat classification for woodland caribou (1 – preferred; 9 – least preferred) and the resulting (B) harvest value for each forest stand using the harvesting heuristic on the Trout Lake forest management unit (light grey – less desirable; black – more desirable).

Figure 4. The predicted (A) mean equivalent connected area (a measure of woodland caribou habitat area and its connectivity) calculated using five movement distances (median movement of 1, 10, 25, 40, 80 km) under four management strategies for no harvesting (solid black), heuristic (dashed black), caribou mosaic (solid grey), and relaxed caribou mosaic (dashed grey) strategies with standard deviation in light grey. Solutions for each movement distance are also shown for (B) no harvesting, (C) harvesting heuristic, (D) caribou mosaic and (E) relaxed caribou mosaic strategies.

Figure 5. The area of habitat in (A) non-harvested and (B) harvested areas over the course of a 100-year planning horizon for each harvesting strategy. Also shown is the number of preferred habitat patches within (C) non-harvested and (D) harvested areas.

Figure 6. Maps showing preferred woodland caribou habitat (black), least-cost links (dark grey), and reserves (light grey) for the terminal landscape (after 100 years of harvest scheduling) for the four harvesting strategies. Harvesting strategies include: (A) no harvesting, (B) harvesting heuristic, (C) caribou mosaic, and (D) relaxed caribou mosaic.

663 **Figure 7.** Stands that are selected for harvest once (light grey), twice (dark grey) and in a few
664 cases, three (black) times over the planning horizon (100 years) using the (A) harvesting
665 heuristic, (B) caribou mosaic, and (C) relaxed caribou mosaic strategies.

666 **Figure 8.** The percent of the Trout Lake Forest Management Unit disturbed for woodland
667 caribou over the course of the planning horizon using the four different harvesting strategies.
668 Here linear features (roads and utility corridors) alongside recently disturbed areas (<20 year old
669 forest) with a 500 m buffer of influence are summed to give the percent area disturbed.

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670 **Figure 1.**

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681 **Figure 4.**

Figure 5.

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698 **Figure 8.**

Supplementary Text

Parameterizing maximum product probability

Maximum product probability (p_{ij}) is defined as the maximum probability of movement across all potential paths between patches i and j , including paths that utilize other patches (Saura et al. 2011). For example, if patches are closer together they will have a maximum product probability of movement that will be a function of direct dispersal between the patches, but if they are further apart it would likely consist of steps through intermediary habitat patches (or stepping stones; see Saura et al. 2011 for details; Figure S3). Using the derived spatial graph based on least-cost paths, we calculated the probability of direct dispersal based on an alpha of 0.5 and a potential median movement distance of 40 km for woodland caribou. While the specific movement distances may differ for woodland caribou depending on the population, season, or region, woodland caribou are highly mobile and travel long distances between areas used for early winter, late winter, spring, calving, and summer. The distances covered between these seasons can vary between approximately 10-25 km in distance apart, for a total annual median distance of movement that is approximately 80 km for populations in northwestern Ontario (Ferguson and Elkie 2004b, a). Further, over the course of a year, the daily median movement rate for woodland caribou can be approximately 1 km per day (Rettie & Messier 2001, Ferguson & Elkie 2004b). We performed a sensitivity analysis of how each of five median movement distances (1, 10, 25, 40 and 80 km) may influence the outcomes of harvesting decisions by our heuristic (see Figure 4 and S4). We find that the overall landscape connectivity (ECA) may differ with median dispersal distance (Figure S4) and that this can translate to differences in the overall amount of habitat found on the landscape (Figure 4). In particular, the amount of habitat available to woodland caribou over the planning horizon is the largest for both 40 km and 80 km

median dispersal distances. Thus, as we are trying to improve and maintain the amount of woodland caribou habitat, we use a median dispersal distance of 40 km for all our subsequent analysis, because 80 km does not provide a measurable improvement over the 100-year planning horizon and 40 km represents a balance between daily, seasonal and annual movement of woodland caribou (Figure 4 and S4; Ferguson and Elkie 2004b, a).

Supplementary Figures

Figure S1. (A) Age class distribution and (B) species composition of forest stands within the Trout Lake Forest Management Unit for the year 2012.

Figure S2. Spatial distribution of harvest under the caribou mosaic harvest scheduling strategy for the Trout Lake Forest Management Unit. Harvest blocks (grey) are stratified temporally for years (A) 1-10 (and 91-100), (B) 11-30, (C) 31-50, (D) 51-70, (E) 71-90 and (F) anytime.

Figure S3. A simple three patch system with three links of direct dispersal. In this case, the probability of direct dispersal between patch A and B is 0.2, but the maximum product probability of dispersal between A and B, using patch C as a stepping stone, is $0.5 \times 0.5 = 0.25$ as this value is greater than the direct dispersal. Adapted from Saura and Pascual-Hortal (2007).

Figure S4. Sensitivity analysis of the Equivalent Connected Area (ECA) metric under five different median dispersal distances (using $\alpha = 0.5$). Shown is the ECA of the initial landscape using different median dispersal distances (1, 10, 25, 40, 80 km).

Figure S5. The equivalent connected area (a measure of habitat connectivity and area) using the harvesting heuristic strategy under different values for both parameters b and c (0.5 and 1) in the Trout Lake Forest Management Unit. Here we hold one value constant at 1 while changing the other. Values are calculated using a median dispersal distance of 40km and alpha value of 0.5.

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