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Prioritizing Areas for Land Conservation and Forest Management Planning for the Threatened Canada Warbler (*Cardellina canadensis*) in the Atlantic Northern Forest of Canada

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Abstract: Populations of Canada Warbler (*Cardellina canadensis*) are declining in Canada's Atlantic Northern Forest. Land conservancies and government agencies are interested in identifying areas to protect populations, while some timber companies wish to manage forests to minimize impacts on Canada Warbler and potentially create future habitat. We developed seven conservation planning scenarios using Zonation software to prioritize candidate areas for permanent land conservation (4 scenarios) or responsible forest management (minimizing species removal during forest harvesting while promoting colonization of regenerated forest; 3 scenarios). Factors used to prioritize areas included Canada Warbler population density, connectivity to protected areas, future climate suitability, anthropogenic disturbance, and recent Canada Warbler observations. We analyzed each scenario for three estimates of natal dispersal distance (5, 10, and 50 km). We found that scenarios assuming large dispersal distances prioritized a few large hotspots, while low dispersal distance scenarios prioritized smaller, broadly distributed areas. For all scenarios, efficiency (proportion of current Canada Warbler population retained per unit area) declined with higher dispersal distance estimates and inclusion of climate change effects in the scenario. Using low dispersal distance scenarios in decision-making offers a more conservative approach to maintaining this species at risk. Given the differences among the scenarios, we encourage conservation planners to evaluate the reliability of dispersal estimates, the influence of habitat connectivity, and future climate suitability when prioritizing areas for conservation.

Keywords: bird distribution and abundance; boreal birds; Canada Warbler; *Cardellina canadensis*; Zonation; reserve design

1. Introduction

Canada Warbler (*Cardellina canadensis*) is a Neotropical migratory songbird that breeds in forests of the eastern U.S. and across Canadian forests from Nova Scotia to the Yukon [1]. Due to ongoing population declines (71% decline reported from 1970–2010 [2]), it is listed as Threatened in Canada [3] and a Species of Greatest Conservation Need in nearly every U.S. state where it breeds (e.g., [4]). The Canada Warbler International Conservation Initiative (CWICI) has urged research and conservation actions to help reverse the population decline, including identification of suitable habitat and development of best management practices for the breeding grounds [5].

In the Atlantic Northern Forest (Bird Conservation Region (BCR) 14), Canada Warbler population declines from 1970–2017 have been much steeper than those observed in other BCRs by the Canadian Breeding Bird Survey [6]. Canada Warblers predominantly use wet forests [7–10] and post-harvest deciduous and mixed-wood forests approximately 10–30 years of age [11,12]. Management guidelines recently produced for BCR 14 [13] (see Supplementary Materials) describe two different approaches to promote recovery of this species: permanent land conservation (hereafter 'land conservation', or 'LC') and responsible forest management (hereafter 'forest management', or 'FM'). These approaches were developed in tandem with, and designed for, two different user communities with distinct needs: (1) land conservancies and government agencies with a mandate to protect species and habitat in situ; and (2) forest industry staff and government agencies with a mandate to engage in sustainable development of forest resources while minimizing impacts to migratory birds and species at risk. LC scenarios (summarized in Westwood et al. [13]) (see Supplementary Materials) are intended to support conservation activities such as in-situ permanent protection of forested areas supporting Canada Warbler populations, forest blocks with low edge-to-interior ratios, and suitable habitat patches connected by forested corridors to other potential breeding sites to facilitate dispersal. FM scenarios are intended to support responsible forest management activities such as providing a continuous current supply of breeding habitat on the landscape, avoiding harvesting and road building in population centers and forested wetlands, and locating areas to implement silvicultural systems (such as shelterwood cutting) most likely to produce desired conditions for breeding habitat 12–20 years post-harvest, among other strategies [13] (see Supplementary Materials).

Forest fragmentation has been postulated as a cause of population declines for this species [14,15], so habitat connectivity on the breeding grounds is likely to play an important role in population recovery, especially given the high degree of conspecific attraction that has been documented [16]. Climate change is another important consideration for Canada Warbler, as its range is expected to retract under warming conditions [17]. Conservation planning software makes it possible to account for connectivity, climate change, and other factors when prioritizing areas for land conservation and forest management [18–20].

Most analyses using conservation planning software are designed to support the planning or evaluation of protected area networks (e.g., [21–23]). Other objectives include locating zones of interest for further study [24], evaluating trade-offs between land uses [25,26], or estimating the value of ecosystem services [27]. Conservation planning algorithms can be informed by estimates of dispersal, which is an important factor in wildlife habitat selection and response to climate change (i.e., the ability to move from current to future suitable habitats). For the Canada Warbler, published estimates of natal dispersal (distance from an individual's birth site to their breeding site) are not available. Estimates of natal dispersal for other passerines are frequently based on small sample sizes with a great deal of uncertainty, and estimates for species of similar sizes to the Canada Warbler range widely [28–31]. Conservation planning exercises are typically based on single dispersal estimates, and the implications of uncertainty in these estimates are unknown. Furthermore, conservation planning algorithms often rely on species distribution models which predict habitat suitability, species occurrence, or population density across a landscape. However, these models are inherently more uncertain in under-sampled areas, and this uncertainty is also not always accounted for during conservation prioritization exercises.

Conservation prioritization exercises are most useful when they directly inform resource allocation decisions across landscapes [32]. Therefore, we consulted a variety of government, conservation, and forest industry stakeholders to develop regional scenarios for prioritization [33] (see Supplementary Materials). We then used the program Zonation [34] to evaluate priority areas for land conservation and forest management to support Canada Warbler populations in the Canadian portion of BCR 14. One set of scenarios was designed to prioritize areas for long-term land conservation (including future climate change and connectivity to protected areas) and another set of scenarios prioritized areas for forest management on tenured land managed by timber companies.

We evaluated three estimates of natal dispersal distance for each set of scenarios. We evaluated the impact of these factors on spatial outcomes and identified areas that were consistently prioritized. We also compared conservation efficiency (proportion of the species' current estimated population protected per unit area) across scenario types and dispersal distance estimates. The resulting rankings of the landscape in BCR14 are intended to support decisions for maintaining and managing Canada Warbler habitat in this region by the two different user groups already described.

2. Materials and Methods

2.1. Study Area

The North American Bird Conservation Initiative (NABCI) defines BCRs as ecologically distinct regions that share similar bird communities, habitats, and resource management issues [35]. We selected the scale of the study as the Canadian portion of the Atlantic Northern Forest (BCR 14) for three reasons. First, BCRs are used by Canadian government agencies as planning and management units for other bird species at risk (e.g., [24,36]). Secondly, the Canada Warbler shows evidence of differential habitat selection across BCRs [37], and we wished to limit the modelling to a population with shared habitat requirements. Finally, limiting the scale of the study to the Canadian portion of the BCR allowed us to use interoperable data and take advantage of existing Canadian bird conservation and forestry networks comprised of government agencies, industry, and NGOs.

The Canadian portion of the Atlantic Northern Forest encompasses 20.4 million ha, including Nova Scotia, Prince Edward Island, New Brunswick, and the Gaspé Peninsula of Québec ([38]; Figure 1). This forest is within the Appalachian-Acadian Ecoregion, which also includes much of Maine and Vermont, and parts of New York and New Hampshire. Human activities in this area have influenced 98.2% of the land area [39].

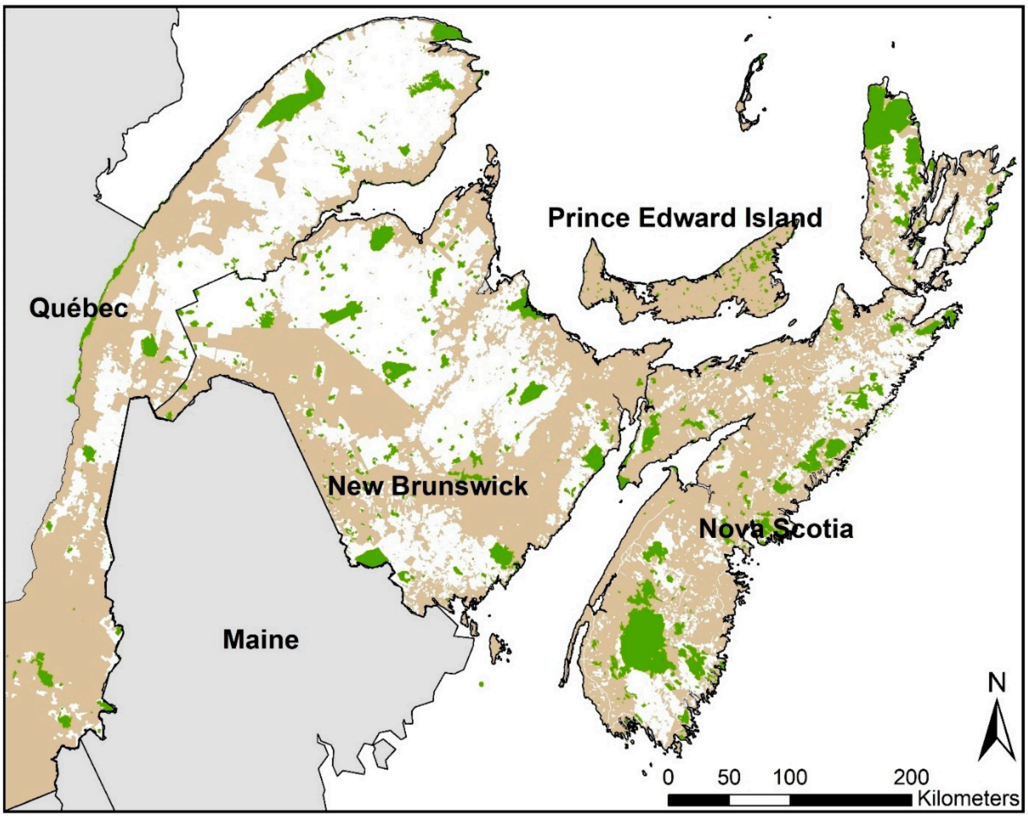

Figure 1. The Canadian portion of the Atlantic Northern Forest (Bird Conservation Region 14) showing protected areas (green) and areas under lease for timber activity (white).

The Atlantic Northern Forest is at the interface of two biomes, and includes tree species from the northern boreal forest (e.g., Black Spruce *Picea mariana*, Eastern White Pine *Pinus strobus*, Balsam Fir *Abies balsamea*) and southern temperate deciduous forest (e.g., Red Spruce *Picea rubens*, Red Maple *Acer rubrum*, Sugar Maple *Acer saccharum*). Land ownership is predominantly private, with the remainder under stewardship of the provinces. Known areas that are permanently protected from development in this region comprise 1.4 million ha (7% of the land area), including national and provincial parks, wilderness areas, and private protected landholdings [40]. Timberlands leased or owned by industrial forestry companies cover 6.7 million ha (33% of the land area). We did not include privately owned woodlots or timberlands in our analyses as we were unable to obtain a comprehensive land use map for such properties.

2.2. Scenario Development

Recent habitat guidelines for Canada Warbler in the Atlantic Northern Forest identified two types of stewardship approaches that could benefit this species: land conservation and forest management [13] (see Supplementary Materials). Based on solicited input from land trust representatives, agency and industrial forest managers, and scientists familiar with Canada Warbler ecology, we developed four scenarios for land conservation and three for forest management (Table 1; see [33] (see Supplementary Materials) for a description of stakeholder engagement and [13] (see Supplementary Materials) for specific details on recommended responsible forest management practices for maintaining Canada Warbler populations on the landscape).

Table 1. Spatial prioritization scenarios developed to support land conservation and forest management planning for Canada Warbler conservation in the Atlantic Northern Forest.

Scenario Group	Scenario Code	Description of Areas Prioritized	Included Data Layers
Land Conservation	LC1	Areas of high current Canada Warbler (CAWA) population density	*CAWA presence 2005–2009, CAWA presence 2010–2015, Population density, Model uncertainty*
	LC2	Areas of high current population density that are connected to protected areas	*CAWA presence 2005–2009, CAWA presence 2010–2015, Population density, Model uncertainty, Protected areas*
	LC3	Areas of high predicted population density under climate change that are connected to areas of high current population density	*CAWA presence 2005–2009, CAWA presence 2010–2015, Population density, Model uncertainty, CAWA climate baseline, CAWA climate 2050*
	LC4	Areas of high predicted population density under climate change that are connected to areas of high current population density and protected areas	*CAWA presence 2005–2009, CAWA presence 2010–2015, Population density, Model uncertainty, Protected areas, CAWA climate baseline, CAWA climate 2050*
Forest Management	FM1	Areas to serve as buffers or reserves during timber harvesting that have high population density and occur in wet forests (assumed to have low timber productivity)	*CAWA presence 2005–2009, CAWA presence 2010–2015, Population density, Model uncertainty, Working lands, Wet-poor habitat*
	FM2	Areas to harvest in upland forest areas (assumed to have high timber productivity) connected to wet forest areas with high Canada Warbler density to encourage colonization at 10–30 years post-harvest	*Population density, Model uncertainty, Working lands, Wet-poor habitat* *Population density, Model uncertainty, Working lands, Wet-poor habitat, Upland habitat, Protected areas*
	FM3	Areas to harvest in upland forest areas (assumed to have high timber productivity) with active avoidance of areas of high population density	*Subtraction of results of FM1 from FM2*

2.3. Zonation Spatial Conservation Prioritization

2.3.1. Data layers and Pre-Processing

To develop the seven scenarios, we acquired input data in three categories: avian, landcover, and administrative boundaries (Table 2).

Table 2. Description of data layers used to generate prioritization scenarios for Canada Warbler in the Atlantic Northern Forest (Bird Conservation Region 14).

Category	Spatial Data Layer	Description	Year Pub-lish-ed	Units	Data Ownership
Administrative Boundaries	Protected areas	The Conservation Areas Reporting and Tracking System geodatabase contains data on national, provincial, and privately-held protected lands, updated on an annual basis.	2015	categories	Canadian Council on Ecological Areas
	BCR14	Canadian portion of Bird Conservation Region 14—Atlantic Northern Forest.	2013	categories	NABCI
	Provinces/states	Federal, provincial, and state administrative regions.	2000	categories	ESRI 2000
	Working lands	Extent of actively leased or owned tenures by forestry companies, including both private and Crown lands.	2014	categories	Global Forest Watch Canada; Environment Canada
	Public lands	Unprotected public hands held by the Crown or other government bodies. May be currently under lease.	2013–2016	categories	Government (Gov't) of Nova Scotia (NS); Gov't of New Brunswick (NB), Gouv't du Québec, Gov't of Prince Edward Island (PEI)
Avian Data	Population density	Mean predicted population density of Canada Warbler in 2014 based predominantly on landcover and disturbance variables.	2013	males/hectare	Boreal Avian Modelling (BAM) Project, Haché et al. 2014
	Model uncertainty	Standard deviation of population density of Canada Warbler in 2014 based predominantly on landcover and disturbance variables.	2013	males/hectare	BAM, Haché et al. 2014
	CAWA presence 2005–2009	Locations where Canada Warblers were observed in point count surveys between 2005–2009.	2015	presence	BAM
	CAWA presence 2010–2015	Locations where Canada Warblers were observed in point count surveys between 2010–2015.	2015	presence	BAM
	CAWA climate baseline	Mean projected population density of Canada Warbler from 1961–1990.	2014	males/hectare	BAM, Stralberg et al. 2015
	CAWA climate 2050	Mean projected population density of Canada Warbler in 2050 based predominantly on climate-related variables.	2014	males/hectare	BAM, Stralberg et al. 2015
Landcover	Water bodies	Provincial hydrographic features at 1:10,000 scale.	2008–2014	N/A	NS Department of Natural Resources; NB Department of Natural Resources/GeoNB (link); Gov't of Québec (pers. comm.); Gov't of PEI;
	Wet-poor habitat	Treed areas categorized as wet-poor by the Northeastern Habitat Types Classification developed for ecosystems and habitats in the Northeast US and Atlantic Canada.	2015	N/A	The Nature Conservancy—Eastern Conservation Science; Ferree and Anderson 201
	Upland habitat	Treed areas categorized as wet-poor by the Northeastern Habitat Types Classification developed for ecosystems and habitats in the Northeast US and Atlantic Canada.	2015	N/A	The Nature Conservancy—Eastern Conservation Science; Ferree and Anderson 2013

Our avian datasets were obtained from the Boreal Avian Modelling (BAM) Project [41–43]. The BAM project holds the largest dataset of boreal and hemiboreal observations of birds in North America and accounts for heterogeneity in survey protocols by correcting abundance estimates for detectability [42]. To determine suspected breeding locations, we divided point occurrences of Canada Warblers into two groups (*CAWA presence 2005–2009* and *CAWA presence 2010–2015*) to capture areas showing persistent observations of Canada Warblers over time. Including recent presence information allows conservation planners to locate areas of high likelihood of extant Canada Warblers to consider for protection, and forest managers to avoid or operations in areas where they may harm, kill, or harass Canada Warbler or their nests or eggs (which are illegal activities under Canada's *Species At Risk Act, S.C. 2002*). To predict *Population density* in a 1 km grid across the study area, we used a national-scale species distribution model for Canada Warbler based on landcover and disturbance data [44]. The standard deviation of the population density estimates across multiple data subsets was used to represent *Model uncertainty*. As Zonation uses an additive approach to discount cell values by uncertainty, we chose a measure of uncertainty in the same units as the population density estimates (standard deviation), rather than using a standardized measure such as coefficient of variation. We note that no data were available on productivity or occupancy for the Canada Warbler in this region, nor fine-scale data to describe habitat characteristics (e.g., Lidar).

To account for projected climate-induced shifts in abundance, we used 4 km population density predictions from models based on climate, land-use, and topography covariates as compared to the baseline population density (detailed description in [45]). *CAWA climate baseline* included predicted population density from 1961–1990. Future projections were for the 2041–2070 time period (*CAWA climate 2050*) based upon a high-end, business-as-usual emissions scenario (A2), averaged over an ensemble of four global climate models from the Coupled Model Intercomparison Project (CMIP3) dataset [46]. Although these future projections do not incorporate anticipated lags in vegetation responses to climate change [17], we considered them a reasonable representation of long-term future habitat suitability for this species, which in this region is projected to experience relatively moderate shifts in density, as opposed to wholesale range shifts [47].

Administrative boundary layers included political and administrative borders (*Provinces/ states* and *BCR14*), known forestry tenures (*Working lands*: lands owned or leased by forestry companies for the purpose of industrial development; [47]), and *Protected areas* meeting any of the International Union for the Conservation of Nature protected areas classifications I-IV (lands protected for long-term biological values, [40]).

Landcover layers included *Water bodies* derived from 1:10,000 aerial imagery and layers of *Wet-poor habitat* and *Upland habitat* (derived from the Northeastern Habitat Types Mapping Initiative; [48]). All spatial data were processed using ArcGIS 10.2.2 [49]. All input and output data layers were rasters in geotiff format with a cell size of 1000 × 1000 m, projected in Canada Lambert Conformal Conic.

2.3.2. Prioritization Analysis

We ran all analyses using Zonation 4.0 [18] with a mask of the land boundaries of the Atlantic Northern Forest (an inverse of the layer *Water bodies*) applied to eliminate oceans and lakes. Detailed run settings and input files are available at https://github.com/borealbirds/cawa-bcr-14. Zonation identifies areas with high concentrations of features, which are the items that are desirable to prioritize for the end use (e.g., population density, land ownership, etc.). Functions are used to apply rules to determine how the features interact and how connectivity between the features are prioritized or penalized [34].

Connectivity functions in Zonation rely on estimates of dispersal distance to determine whether features or populations are 'connected.' Due to scarce species-specific dispersal data, Carroll et al. [50] completed a prioritization analysis using an estimated dispersal distance (not specific to natal or breeding) of 10 km for landbird species. For Canada Warbler, there are no published natal dispersal estimates and only one known direct observation (10 km; L. Reitsma, unpublished data). Because natal dispersal distances of landbirds are correlated with wing length and body mass [29,30], the Canada Warbler's average size (wing span = 20–22 cm, mass = 9.5–12.5 g; Reitsma et al. 2010) suggests a median dispersal distance of 50 km [30]. However, estimates for similar-sized species vary widely, from 0.5 km to 40 km [28–31]. Betts et al. [51] measured maximum breeding dispersal distances of 1–3 km for two species of forest-dwelling warblers whose ranges overlap that of Canada Warbler (the Black-throated Blue Warbler, *Setophaga caerulescens*, and the Blackburnian Warbler, *Setophaga fusca*). To account for the uncertainty regarding dispersal estimates for this species and capture the variation in dispersal estimates for similar species, we evaluated three different natal dispersal estimates for each scenario: low dispersal distance (LDD, 5 km), medium dispersal distance (MDD, 10 km), and high dispersal distance (HDD, 50 km).

Zonation uses three primary algorithms to prioritize raster cells for selection: core area zonation (CAZ), additive benefit function, and targets [18]. In this case we did not have an a priori conservation target, which is one reason we chose Zonation over the similar software Marxan [19], which requires proportional or area targets as inputs. We chose CAZ because it ensures that the most valuable areas for each feature ("core areas") are prioritized, rather than allowing trade-offs between features, as is the case with additive benefit functions. In each iteration of the algorithm, CAZ chooses the cell with the lowest retention value as specified by the features and connectivity functions, discards it, and then recalculates the value of all remaining cells. In this way, each cell is ranked in order of its priority for selection, with the first cells selected being lowest priority and the last cells being highest priority [18].

For scenario LC1, we input the *Population density* feature (weight 1.0). In Zonation, features are generally given a standard weight of 1.0 unless they are to be discounted due to uncertainty (such as future climate projections) or increased in value due to particular management objectives [18]. We then applied the 'Distribution Smoothing' function to aggregate areas with cells of high population density connected by dispersal ability of Canada Warbler (dispersal kernel specified by α [18]; LDD = 5 km, $\alpha = 4 \times 10^{-4}$; MDD = 10 km, $\alpha = 2 \times 10^{-4}$ HDD = 50 km, $\alpha = 4 \times 10^{-5}$). The 'Species of Special Interest' function was used to increase the value of cells overlapping with *CAWA presence 2005–2009* and/or *CAWA presence 2010–2015.* Finally, we subtracted calculated *Model uncertainty* from all cells. After applying all features and functions, cells were prioritized for selection by the CAZ algorithm. LC2 included all features and functions from LC1. We then added *Protected areas* as a feature (weight 1.0) and used 'Matrix Connectivity' to prioritize selection of cells containing high Canada Warbler densities within 5 km of protected areas (distance specified by applying weighting factor = 0.1). The 'Matrix Connectivity' function multiplies the value of a cell based on its connectivity to other specified features, with features being considered connected if they fall within the specified dispersal distance [18].

LC3 included all features and functions from LC1 with the addition of the 'Ecological Interactions' function, which prioritizes areas based on connectivity between a pair of features [18]. We thus prioritized areas where high densities of Canada Warbler in both *CAWA climate baseline* (weight 0.75) and *CAWA climate 2050* (weight 0.75) were connected based on dispersal distance over 36 years (dispersal ability kernel is represented by β [18]; LDD = 5 km dispersal/year, 180 km total, $\beta = 1.1 \times 10^{-5}$; MDD = 10 km dispersal/year, 360 km total, $\beta = 5.56 \times 10^{-6}$; HDD = 50 km dispersal/year, 1800 km total, $\beta = 1.1 \times 10^{-6}$). We weighted climate features at 0.75 because assumptions about the future are less certain than present estimates (Moilanen and Arponen 2011). LC4 included all features and functions from LC2, with the addition of the 'Ecological Interactions' function used in LC3, in order to prioritize areas connecting high current and future populations of Canada Warbler with each other and with *Protected areas*.

FM1 included all features and functions from LC1 and added the 'Administrative Units' function, which recognizes that conservation decisions can be limited by administrative boundaries [18]. *Working lands* were given a weight of 0.5 to prioritize these areas for selection while maintaining connectivity with outside areas. The 'Matrix Connectivity' function was used to prioritize areas connecting high population density and *Wet-poor habitat.* FM2 included all features and functions from LC1 while omitting the 'Species of Special Interest' function to avoid prioritizing cells with Canada Warbler occurrences. 'Matrix Connectivity' was added to prioritize areas connecting high population density and *Upland habitat* (weight = 0.5). This function is based on the assumption that upland areas have desirable timber value and a greater potential to support Canada Warbler populations in 10–30 years after harvest if connected to dispersal sources and managed appropriately [13] (see Supplementary Materials). We added a second 'Matrix Connectivity' function to disincentivize prioritization of areas connecting high population density with *Wet-poor habitat* (weight = −0.5), and a third 'Matrix Connectivity' function deterring prioritization of areas connecting high population density with *Protected areas* (weight = −0.5).

FM3 was not completed in Zonation, but rather was derived by subtracting the FM2 solution raster from the FM1 solution raster in ArcGIS. This was intended to identify areas for timber harvest with the lowest risk of harm to populations and maximum economic opportunity.

2.3.3. Scenario Comparisons

For scenarios LC1–4 and FM1–2, we plotted performance curves representing conservation efficiency (the proportion of current predicted Canada Warbler population protected as a function of area protected, or not harvested in the case of FM2, at each dispersal distance estimate). Because of the different objectives of the scenarios, and functions applied, it was not sensible to compare conservation efficiency of all scenarios. We compared efficiency curves for scenarios with and without climate change but with all other factors being equal (LC2 and LC4). We also compared FM1 and FM2. Finally, we compared mean differences in cell-level rankings for all land conservation scenarios and estimated dispersal distances.

3. Results

For high resolution maps and data for all scenarios, visit https://github.com/borealbirds/cawa-bcr-14. Of the land conservation scenarios (Figure 2), areas that were consistently prioritized in both current and future climate scenarios included lands in central New Brunswick and the southeastern part of Québec along the border with Maine. All land conservation scenarios prioritized cells with recent and repeated observations of Canada Warbler, but these cells had a minimal effect on conservation efficiency or overall distribution of priority areas (e.g., Figure 3). Relatively few areas in Nova Scotia were prioritized in both current and future climate scenarios, except for small areas close to two large national parks. Adding connectivity to protected areas had little impact on the geographic distribution of areas prioritized in the current climate scenario (LC2), but had a more dramatic effect in the future climate scenario (LC4).

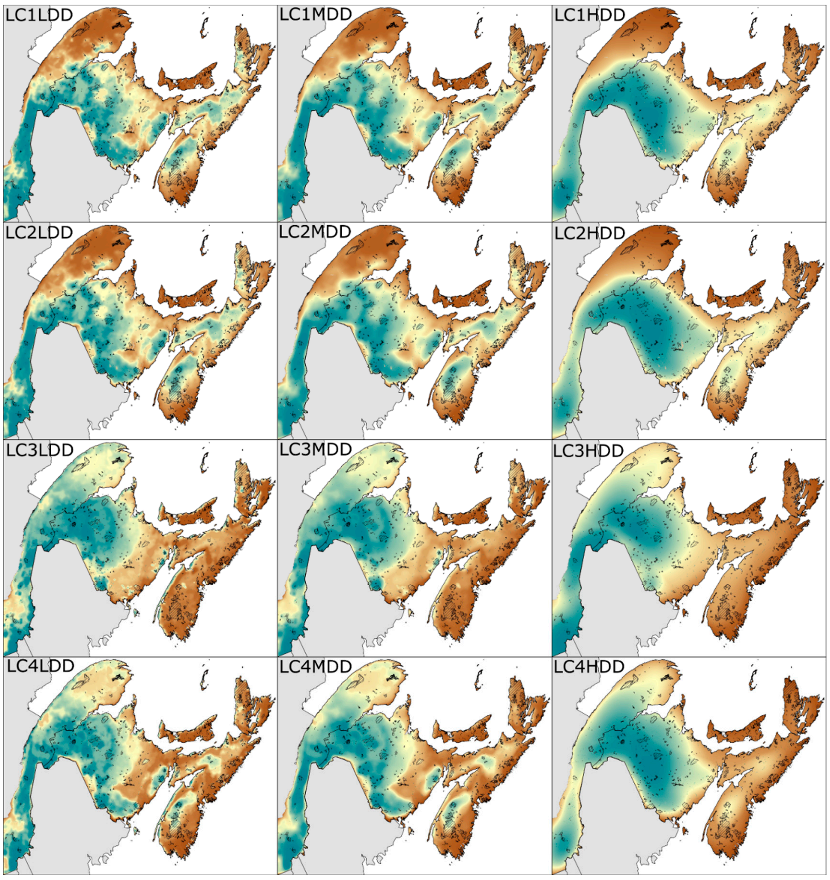

Figure 2. Zonation scenarios to prioritize areas for land conservation for Canada Warbler in Bird Conservation Region 14 at three natal dispersal distances: low dispersal distance (LDD, 5 km), medium dispersal distance (MDD, 10 km), and high dispersal distance (HDD, 50 km). Scenario descriptions given in Table 1. Priority rank for conservation scaled from blue (highest) to brown (lowest). Protected areas indicated by outlined polygons.

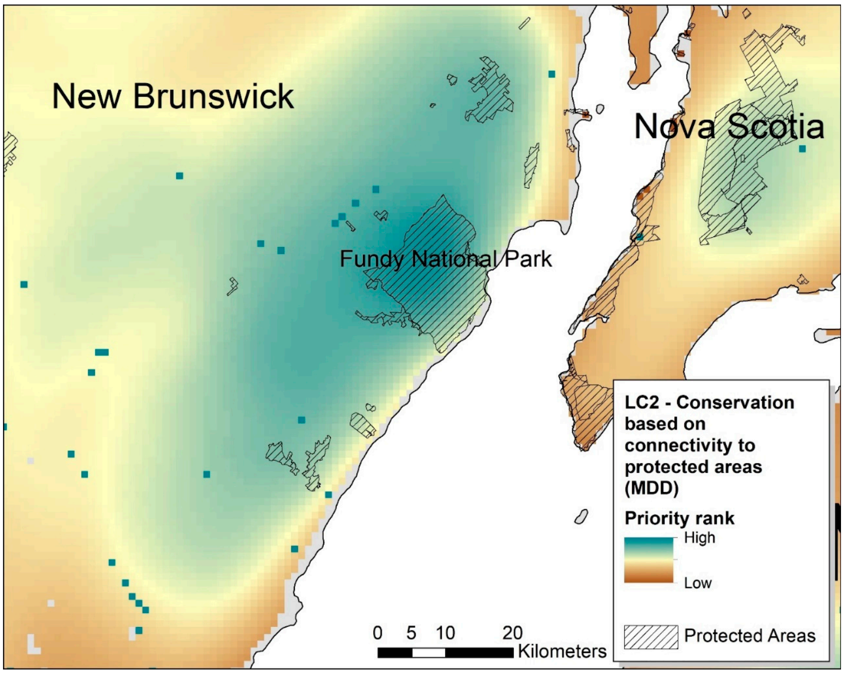

Figure 3. Zonation scenario to prioritize areas for land conservation with high current population density of Canada Warbler which are connected to protected areas at a medium natal dispersal distance (10 km). Crosshatched polygons indicate protected areas. Blue squares were highly prioritized because they included observations of Canada Warbler made during point count surveys between 2005 and 2015.

Increasing the dispersal distance estimate increased the aggregation of prioritized areas, with clusters of priority sites being larger and fewer in number for high dispersal distance scenarios, and smaller and more widely distributed for low dispersal distance scenarios (Figure 2). Overall, in the high dispersal distance scenarios, areas in Nova Scotia were rarely prioritized, with the largest aggregations of prioritized cells occurring in central New Brunswick, and to a lesser extent, southeastern Québec for current climate scenarios, and almost exclusively in Québec for future climate scenarios.

With the forest management scenarios (Figure 4), the emphasis was on forestry tenures; thus results are most appropriately applied by individual managers to compare the relative values of areas within those tenures when considering where to engage in responsible forest management practices (guidance is available in an accompanying technical report [33]) (see Supplementary Materials). Both FM1 and FM2 were affected by dispersal distance, shifting from many prioritized areas in Québec under LDD and MDD scenarios to prioritizing almost exclusively areas in New Brunswick under HDD scenarios.

When subtracting retention areas (FM1) from harvest priorities (FM2), the resulting scenario FM3 indicated that areas in the northern Gaspé Peninsula of Québec would be most effective at maximizing harvest value while minimizing potential loss of Canada Warbler. As with the land conservation scenarios, the prioritized areas were more aggregated with increased dispersal distance.

Scenario Comparison

For all scenarios, efficiency (proportion of current predicted Canada Warbler population retained per unit area) declined with higher dispersal distance estimates. Including climate change reduced land conservation scenario efficiency with respect to the current population (Figure 5). Efficiency was not directly comparable between forest management and land conservation scenarios due to differing objectives, as evidenced by the inverted efficiency curves for FM1 and FM2 (Figure 5), the former of which was designed to prioritize areas to avoid during forest management with the latter prioritizing areas to target for harvesting.

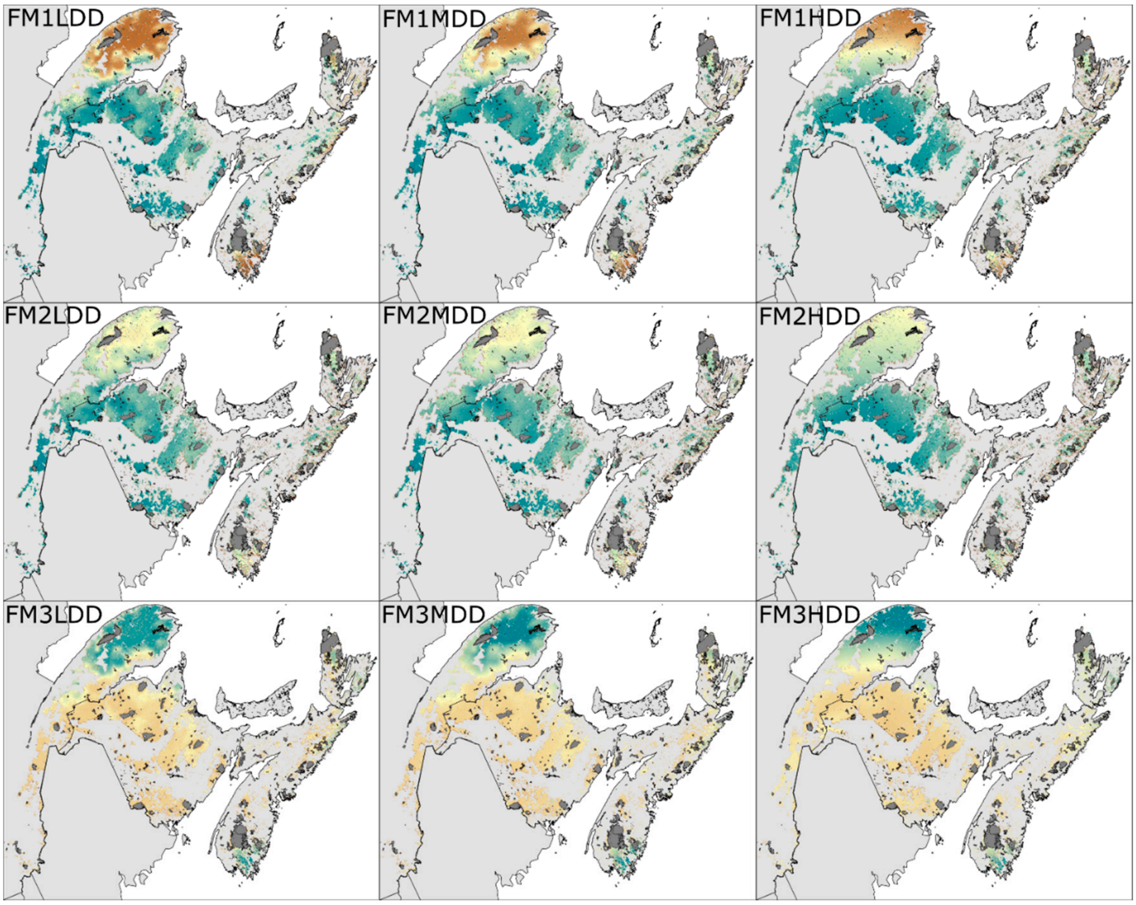

Figure 4. Zonation scenarios to prioritize areas for responsible forest management for Canada Warbler within forestry tenures in Bird Conservation Region 14 at three natal dispersal distances: 5 km (LDD), 10 km (MDD), and 50 km (HDD). Scenario descriptions given in Table 1. Priority rank for management scaled from blue (highest) to brown (lowest). Protected areas indicated by gray polygons.

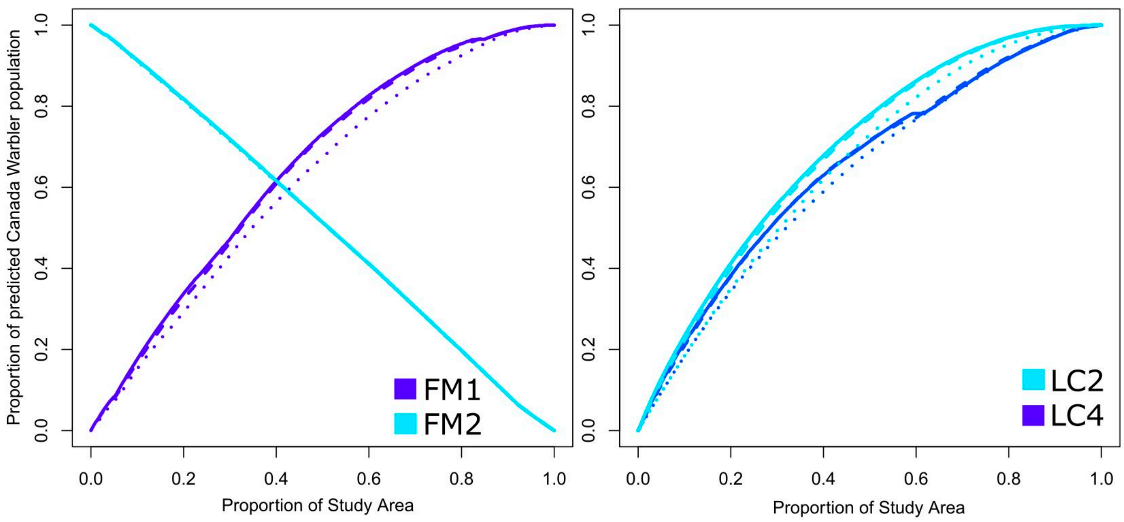

Figure 5. Response curves comparing efficiency (proportion of Canada Warbler population density retained per unit area) for two forest management scenarios (left panel) and two land conservation scenarios (right panel). Scenario descriptions given in Table 1. Curves shown at three dispersal distances: 5 km (LDD, solid line), 10 km (MDD, hashed line), and 50 km (HDD, dotted line).

For land conservation scenarios, cell-level rankings, which range from 0 to 1, differed more between MDD and HDD scenarios (mean = 0.10, SD = 0.90) than between LDD and MDD scenarios (mean = 0.04, SD = 0.04), with greater variation in differences also found between MDD and HDD (Table 3).

Table 3. Percent change in mean cell-level rankings across Zonation prioritization scenarios to support land conservation for the Canada Warbler when comparing between different estimated dispersal distances: 5 km (LDD), 10 km (MDDs), and 50 km (HDD). Scenario descriptions given in Table 1.

Scenario	Dispersal Estimates Compared	Mean Percent Change in Priority Ranking of a Given Cell between Scenarios	Standard Deviation of Percent Change in Priority Ranking
LC1	MDD-LDD	3	3
LC1	HDD-MDD	9	7
LC2	MDD-LDD	4	4
LC2	HDD-MDD	12	9
LC3	MDD-LDD	3	4
LC3	HDD-MDD	7	7
LC4	MDD-LDD	4	5
LC4	HDD-MDD	12	11

4. Discussion

We generated land conservation and forest management prioritization maps for the Canada Warbler in the Canadian portion of the Atlantic Northern Forest. This exercise identified several consistently prioritized areas for a range of stewardship objectives. In particular, central New Brunswick and southern Québec emerged as important areas for conservation and management under both current and future climate scenarios and when considering a range of possible dispersal distances. In general, areas farther from the coast were more frequently prioritized for conservation. Including projected effects of climate change on potential population density had dramatic effects in the scenarios, leading to almost no areas prioritized for conservation in Nova Scotia, and shifting priority areas northward. Within forest management tenures, the northern Gaspé Peninsula of Québec was consistently identified as the area where forest harvesting activities may be most practical while avoiding impacts to current Canada Warbler populations. This is consistent with Sólymos et al. [44], who predicted a lower average Canada Warbler population density in the Gaspé Peninsula compared to the rest of the study area.

Given this species' high conservation concern, our single-species exercise has potential to aid the rapid implementation of conservation and recovery action. Our method was somewhat unique in that landscape prioritization exercises are typically used for the assessment of biodiversity at large scales considering many different species (e.g., [19,51]). For a given taxon, Zonation results that are produced using only survey data could be different from those using species distribution models [52] and including both as input features may offer benefits. Although in our case adding recent locations of Canada Warbler only had a small impact on the overall solution, important differences were apparent at the level of individual cells (1 km^2). Including this element is critical for land managers making decisions on small scales, as they indicate land parcels with persistent occupancy by Canada Warblers. These areas can thus be targeted for permanent land conservation and avoided during forest harvesting.

Although our prioritization scenarios provide insight into possible locations to target conservation and management activities, the spatial resolution of the scenarios (1 km) is too coarse to identify specific habitat patches. While two finer-scale Canada Warbler species distribution models have been constructed in this region [10,53], their coverage does not include the entire study area. Prioritized areas should be regarded as suggestions that require more detailed investigation through comparison with satellite imagery and ground-truthing before being considered candidates for conservation or management activity. To maximize efficacy, our analysis should be repeated as finer-scale spatial data become available to support local management planning and to account for the small territory sizes of the Canada Warbler (average 1 ha; [16,54]).

4.1. Accounting for Uncertainty

The predictions made by species distribution models, frequently used as input features in conservation prioritization exercises, are inherently more uncertain in under-sampled areas [55,56]. We accounted for this uncertainty by discounting densities by the standard deviation of mean population density, and thus were able to focus priorities on areas of lower scenario uncertainty [24,57].

We also attempted to account for uncertainty about dispersal distances within Canada Warbler populations by evaluating each scenario using three different dispersal distance estimates. These estimates were intended to influence results by dictating the extent to which priority conservation and management areas were required to be in close proximity to protected areas and known Canada Warbler locations, and to influence the allowed distance between current and future projected Canada Warbler distributions. However, we also used dispersal distance estimates within Zonation's 'Distribution Smoothing' function, which aggregates priority areas based on the assumption that fragmented solutions are undesirable [18], thereby yielding results that were increasingly spatially aggregated with larger dispersal distance estimates. This led to large differences in geographic priorities across scenarios, suggesting the need for careful consideration of habitat connectivity requirements for Canada Warbler and other species of conservation concern. Given that dispersal is a key parameter in spatial conservation prioritization [50], our findings highlight the importance of considering a range of dispersal assumptions. Future studies may benefit from multiple scenarios designed to isolate the different ways in which dispersal estimates can influence results.

The increased level of spatial aggregation in conservation priorities with higher dispersal estimates led to less efficient solutions in terms of the current predicted Canada Warbler population that would be conserved per unit area. However, conservation efficiency was influenced less by assumptions about dispersal distance than by assumptions about climate change effects on species' distributions, due to the large discrepancies between predicted current and future suitable habitats for boreal species [17]. Our results are consistent with those of Stralberg et al. [24], who found that incorporating potential avian responses to climate change reduced conservation efficiency for current songbird populations. This supports the idea that planning to incorporate climate change increases the size required for protected areas to adequately conserve species [17,58,59].

4.2. Maintaining Viable Populations on the Landscape

Connectivity was important in identifying management opportunities through this prioritization effort because Canada Warblers cluster in multi-territory "neighborhoods" [16,60]. Canada Warblers use forest stands post-harvest more often if they are within 100 m of unharvested stands with conspecific breeders; in one study, the presence of conspecifics was found to be more important than habitat condition for predicting stand use [16]. Therefore, it is important to conserve or manage for areas of sufficient size to support a neighborhood, although the ideal size and configuration of such habitat patches is not yet known. It is also not known whether dispersal within and between such neighborhoods is important for Canada Warbler population viability, nor what barriers to functional connectivity [61] exist for this species in this region. However, observed population declines combined with stable breeding productivity [62] suggest that eastern populations may not be limited by quality or connectivity of breeding habitat.

Our scenarios that assumed a high dispersal distance (HDD) prioritized large areas in the northwest portion of the study region. In contrast, the low dispersal distance (LDD) scenarios prioritized more locations of smaller size across the Atlantic Northern Forest. Relying on the results from HDD scenarios alone could undermine the goals of individual provinces to maintain native species by favoring the conservation of fewer large populations rather than a larger number of small, spatially distributed populations. The latter may be preferable from the standpoint of maintaining genetic variability across the landscape [63]. Furthermore, our scenarios that considered future climate projections (particularly the HDD variants) assigned low priority to southern populations in Nova Scotia and southern Québec—areas that become less hospitable to Canada Warbler in a warmer climate. Thus, the LDD and current climate scenarios represent more conservative assumptions for conservation and management. This may be more appropriate for a species that is experiencing population declines, especially given range-wide projected increases in habitat suitability under climate change [17].

To guarantee long-term persistence of high-quality breeding areas for the Canada Warbler, information on the capacity of habitats to support viable populations through detailed spatial population viability analyses is critical [64]. Although Zonation uses connectivity of populations as a surrogate for viability [20], this may not be as relevant for passerines, who have greater mobility than taxa with small dispersal distances such as small mammals, plants, or colonial birds. By incorporating measures of connectivity and including recent and repeated observations of Canada Warblers to locate high priority areas, we may have been able to better prioritize the landscape for conservation of high-value habitat than what was accomplished by using species distribution models or survey data alone. We were not able to include data on habitat selection and reproductive success that may have given a more direct indicator of population viability, which is being used in ongoing studies (Burns & Reitsma, in revision; Amelie Roberto-Charron, pers. comm.; Junior Tremblay, pers. comm.). Future prioritization efforts should include results of assessments of reproductive success and population viability wherever possible in order to most accurately target areas to maintain population density on the landscape. Such data would be particularly valuable if comparing harvested and unharvested areas, to test the hypothesis of whether areas undergoing forest management represent ecological traps for this species [65].

The present study advances the understanding of conservation issues and management opportunities for Canada Warbler at a regional scale. Our results help to define priority areas for Canada Warbler land conservation and forest management, and in conjunction with the habitat guidelines for the Canadian portion of the Atlantic Northern Forest [13] (see Supplementary Materials), they provide a toolkit for managers to immediately locate areas for implementing conservation and management actions. We suggest that this approach, designed to support management objectives for a single species, be applied to other species. We particularly encourage managers to apply this prioritization approach to Canada Warbler populations in other BCRs in Canada and the U.S. to support persistence of the entire breeding population.

Supplementary Materials: The following are available online at http://www.mdpi.com/1424-2818/12/2/61/s1, file 1: Westwood et al—2017—Guidelines for managing Canada Warbler habitat.pdf; file 2: Westwood, Reitsma, Lambert—2017—Prioritizing areas for Canada Warbler conservation and management.pdf.

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