Estimating Minimum Dynamic Reserves for Ecoregions in the Northwest Boreal LCC Planning Region

Prepared by the BEACONs Project, University of Alberta - Marc Edwards, Pierre Vernier, and Kim Lisgo
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INTRODUCTION

The objective of this analysis was to identify Minimum Dynamic Reserves (MDRs) for ecoregions within the Northwest Boreal Landscape Conservation Cooperative (NWBLCC) planning region. MDRs define the "minimum reserve area required to incorporate natural disturbance and maintain ecological processes" (Leroux *et al.* 2007), and are used to inform the minimum size for ecological benchmarks. Ecological benchmarks are control sites against which the effects of management decisions can be monitored and evaluated within an adaptive management framework. As control sites, ecological benchmarks support an environment where biotic and abiotic processes operate free of human interference. This requires that benchmarks be of sufficient size to capture and maintain processes that shape landscapes at broad spatial extents over long-time frames. Across the boreal, natural disturbances such as fire and insect outbreaks play a significant role in shaping landscape structure and the adaptations of many organisms (*e.g.*, Weber and Stocks 1998; Bond and Keeley 2005). By capturing and maintaining natural disturbance regimes, benchmarks can support the persistence and natural function of species and processes operating at finer scales. In addition to representing natural disturbances, benchmarks must be of sufficient size to experience large, severe natural disturbance events while maintaining internal recolonization sources for vulnerable vegetation types. Internal recolonization sources are lifeboats for species reliant on vulnerable habitats such as flammable vegetation types. By maintaining these lifeboats, the benchmark can continuously support effective monitoring of biodiversity and the implementation of adaptive management.

Inspired by the concept of Minimum Dynamic Areas (Pickett and Thompson 1978), Leroux *et al*. (2007) developed methods for estimating benchmark size in fire-dominated regions with the goal of meeting the size objectives described above. Here, we use historic fire records, distributions of flammable vegetation types, and the dynamic landscape simulation software CONSERV (BEACONs 2015, Leroux *et al.* 2007) to identify MDRs to support the identification of ecological benchmarks for the NWBLCC planning region.

METHODS

This section describes the study area, and the general methods used to create input data, estimate fire parameters, and develop the succession matrix used in CONSERV. Additional details about the procedures can be found in Appendices 1 and 2.

Study Area

The study area is defined by the NWBLCC boundary. To identify MDRs, we stratified the study area into ecoregions (Figure 1). There are three ecoregion maps available for Alaska, and we used the Unified Ecoregions of Alaska (Nowicki *et al*. 2001), which aligns well with the National Ecological Framework of Canada (Marshall *et al*. 1999). All ecoregions that fell largely within the NWBLCC study area were included in the analysis (Figure 1, Table 1). Ecoregions within only a small portion within the NWBLCC study area were excluded (*e.g.*, ecoregion 30 - Yukon-Kuskokwim Delta).

Ecoregion 23 (North Ogilvie Mountains) is characterized by a distinct vegetation change between the east and west portions of the ecoregion. MDR results in such situations can produce inflated values. We therefore split this ecoregion into two planning units based on the underlying ecodistrict boundaries

(Figure 2). Results are presented for the full extent of ecoregion 23, as well as for the two sub-regions 23a and 23b. For ease of communication, 23a and 23b are referred to as ecoregions. A complete list of ecoregions used in the analysis is shown in Table 1.

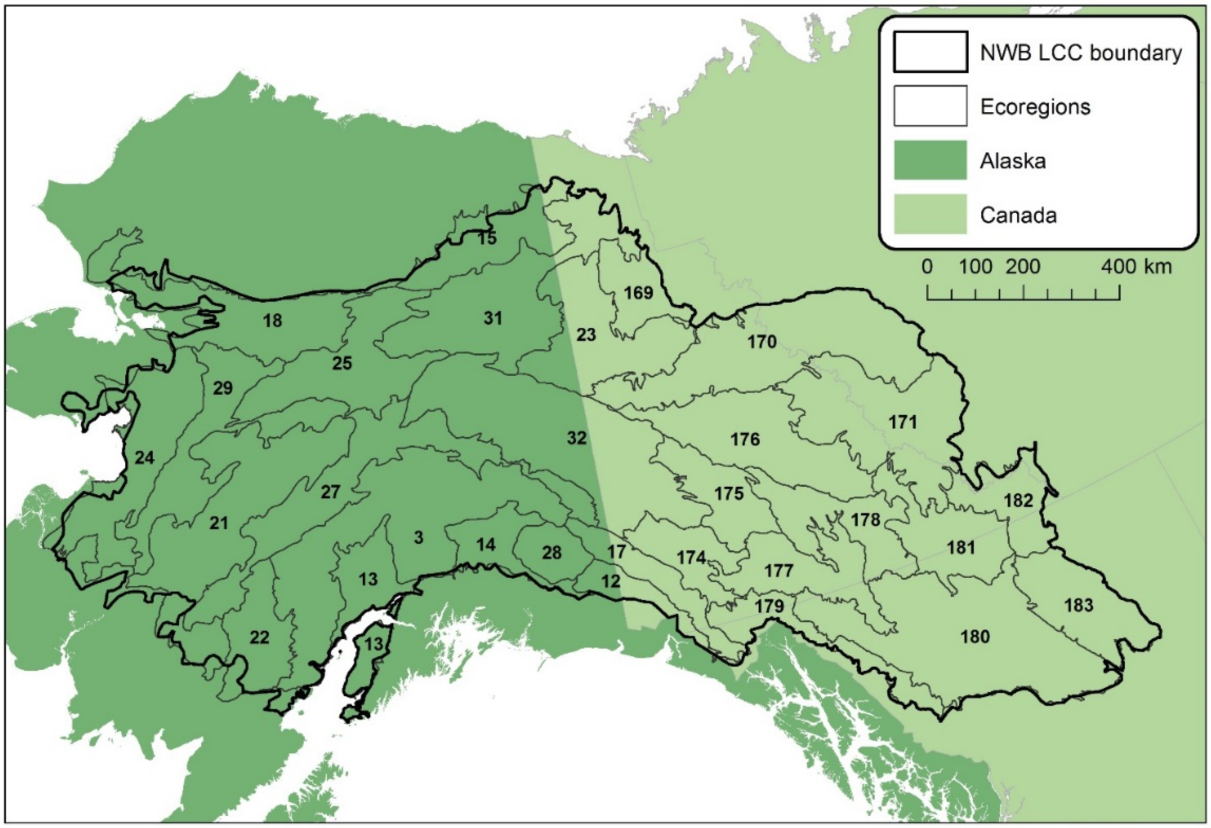


Figure 1. Minimum Dynamic Reserve sizes were estimated for the 29 ecoregions intersecting the Northwest Boreal LCC planning region. Ecoregion labels correspond to names in Table 1. Ecoregion 23 was partitioned into two sub-regions for analysis as described in Figure 2.

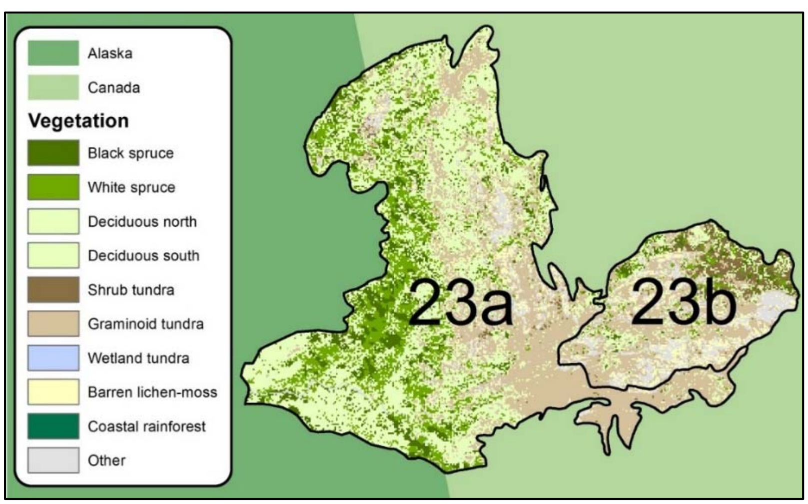


Figure 2. The North Ogilvie Mountains ecoregion was split into two separate planning units based on the underlying ecodistrict boundaries. Results were generated for the full ecoregion (23), as well as for the two sub-regions 23a and 23b.

Table 1. Main ecoregions comprising the NWBLCC study area based on Unified Ecoregions of Alaska (Nowicki *et al*. 2001) and the National Ecological Framework of Canada (Marshall *et al*. 1999).

Region	**Ecoregion**	**Code**	**Area (km^2)**
Alaska	Alaska Range	3	103,327
	Cook Inlet Basin	13	29,027
	Copper River Basin	14	19,137
	Kobuk Ridges and Valleys	18	55,128
	Kuskokwim Mountains	21	85,354
	Lime Hills	22	28,713
	Nulato Hills	24	58,127
	Ray Mountains	25	51,239
	Tanana-Kuskokwim Lowlands	27	64,011
	Wrangell Mountains	28	14,313
	Yukon River Lowlands	29	51,726
Transboundary	Chugach-St. Elias Mountains	12	13,315
	Davidson Mountain	15	33,731
	Kluane Range	17	20,923
	North Ogilvie Mountains	23/23a/23b	52,160
	Yukon-Old Crow Basin	31	72,731
	Yukon-Tanana Uplands	32	102,489
Canada	Eagle Plains	169	20,540
	MacKenzie Mountains	170	87,067
	Selwynn Mountains	171	72,426
	Ruby Ranges	174	22,867
	Yukon Plateau-Central	175	26,986
	Yukon Plateau-North	176	57,428
	Yukon Southern Lakes	177	35,868
	Pelly Mountains	178	35,526
	Yukon-Stikine Highlands	179	24,849
	Boreal Mountains and Plateaus	180	105,582
	Liard Basin	181	34,466
	Hyland Highlands	182	26,076
	Northern Canadian Rocky Mountains	183	37,830

Data Sources

We used several datasets to estimate MDRs including landcover, forest age, and fire history (Tables 2 and 3). To simulate vegetation, CONSERV requires a vegetation succession matrix and a minimum of two input grids in ASCII format: 1) a categorical landcover map consisting of static landcover classes (*e.g.*, lakes) and dynamic classes (*e.g.*, forest), and 2) a continuous forest age map consisting of annual stand age or time since disturbance. To simulate fire, CONSERV also requires four parameters of fire behavior derived from historic fire databases.

Datasets were identified and acquired in collaboration with NWBLCC partners. Datasets that were available separately for Alaska and Canada (*e.g.*, fire history) were combined into a seamless coverage. For analysis, all vector datasets were converted to rasters, projected to Alaska Albers, resampled to a 1-km^2 pixel size, and snapped to the ecoregion raster. The pixel size for all raster datasets was set at 1 km^2 to match the landcover data. Where required, values were assigned to pixels using nearest neighbor.

Table 2. Alaska datasets used to estimate MDRs.

Dataset	Source	Type	Resolution	Year
Ecoregions	Unified Ecoregions of Alaska (Nowacki *et al.* 2001)[a]	Vector	1:2,500,000	2001
Fire	Alaska Large Fire Database[b]	Vector	NA	1940-2014
Landcover	Land Cover v2.0 (SNAP 2015a)[c]	Raster	1 km^2	2005
Aspect	Elevation (SNAP 2015b)[d]	Raster	1 km^2	1996
Forest age	Pan *et al*. (2011)	Raster	250m	updated 2011
Lakes	Alaska Hydrography 1:63,360 (Alaska Department of Natural Resources 2007)[e]	Vector	1:63,360	2007

[a] Alaska Geospatial Data Committee http://agdc.usgs.gov/data/usgs/erosafo/ecoreg/
[b] https://www.frames.gov/catalog/10465 (downloaded December 11, 2014).
[c] SNAP (Scenarios Network for Alaska and Arctic Planning) http://www.snap.uaf.edu/data.php
[d] SNAP (Scenarios Network for Alaska and Arctic Planning) http://ckan.snap.uaf.edu/dataset/elevation
[e] URL: http://dnr.alaska.gov/mdfiles/hydro_63360.html

Table 3. Canadian datasets used to estimate MDRs.

Dataset	Source	Type	Resolution	Year
Ecoregions	National Ecological Framework of Canada (Marshall *et al.* 1999)	Vector	1:7,500,000	1995
Fire history	Canadian National Fire Database (CNFB; NRCan2014)[a]	Vector	NA	1940-2014
Landcover	North American Land Cover 2005 (CEC 2013)	Raster	1 km^2	2010
Aspect	Elevation (SNAP 2015b)[b] and Canada3D DEM (NRCan 2002)[c]	Raster	1 km^2	1996
Forest age	Pan *et al*. (2011); Alaska 2006 and Canada 2004[d]	Raster	250m	updated 2011
Lakes	Atlas of Canada, hydrology layers (NRCan 2009)	Vector	1:1,000,000	2008

[a] http://cwfis.cfs.nrcan.gc.ca/ha/nfdb
[b] SNAP (Scenarios Network for Alaska and Arctic Planning) http://ckan.snap.uaf.edu/dataset/elevation
[c] Digital elevation model of the Canadian Landmass - Canada3D http://open.canada.ca/data/en/dataset/042f4628-94b2-40ac-9bc1-ca3ac2a27d82
[d] NASA Spatial Data Access Tool https://webmap.ornl.gov/ogc/dataset.jsp?ds_id=1096

Vegetation

The vegetation succession model identified for this analysis, and described later in this document, is based on six land cover classes: black spruce, white spruce, deciduous, shrub tundra, and graminoid tundra. These are the same land cover classes that have been used to model boreal landscapes in Alaska with the modelling software ALFRESCO (*e.g.*, Rupp *et al.* 2002). For analysis, we further partitioned deciduous into north- and south-facing, as explained later.

Alaska. Several landcover maps are available for Alaska; however, at the time of analysis, only the land cover dataset developed by the ALFRESCO modelling group differentiated conifer classes into black and white spruce (Land Cover v2.0; Table 2). For analysis, we modified Land Cover v2.0 by splitting the deciduous class into north and south facing classes to accommodate the succession matrix, using a reclassified aspect grid, derived from elevation data (SNAP 2015b; Table 2) with north aspect = 300 – 90 degrees and south aspect = 90 – 300 degrees. The map has a resolution of 1 km^2.

Canada. Land Cover v2.0 covered most the NWBLCC study region, except for the Northwest Territories (NWT; Figure 3). To fill this hole in the coverage, we used the methods described in Cihlar *et al.* (1996) and Calef *et al.* (2005) to reclassify the 2005 North American Land Cover (CEC 2013). Aspect for the NWT was derived from the Canada 3D digital elevation model (NRCan 2002; Table 3). Detailed methods are described in Appendix 2.

Forest Age

Alaska. Forest age in Alaska was described using the 2006 1-km2 forest age map of Pan *et al*. (2011), updated to 2011 and 250-m resolution (Kevin McCullough, USDA Forest Service, personal communication; Figure 4). We resampled the age map to 1-km^2 using the nearest neighbor method to match the pixel size of the vegetation map.

Canada. To match the Alaska age map, we updated the Pan et al.'s (2011) 2004 forest age map for Canada to 2011. This was done in two steps. First, we aged the 2004 map by adding 6 years to all pixels. Then, we used a rasterized version of the fire history polygon dataset (Table 3, NFDB) to sequentially reset age pixels that burned between 2004 and 2011 to the correct age (*e.g.*, a pixel that burned in 2011 would have age 0, a pixel that burned in 2006 would have age 5).

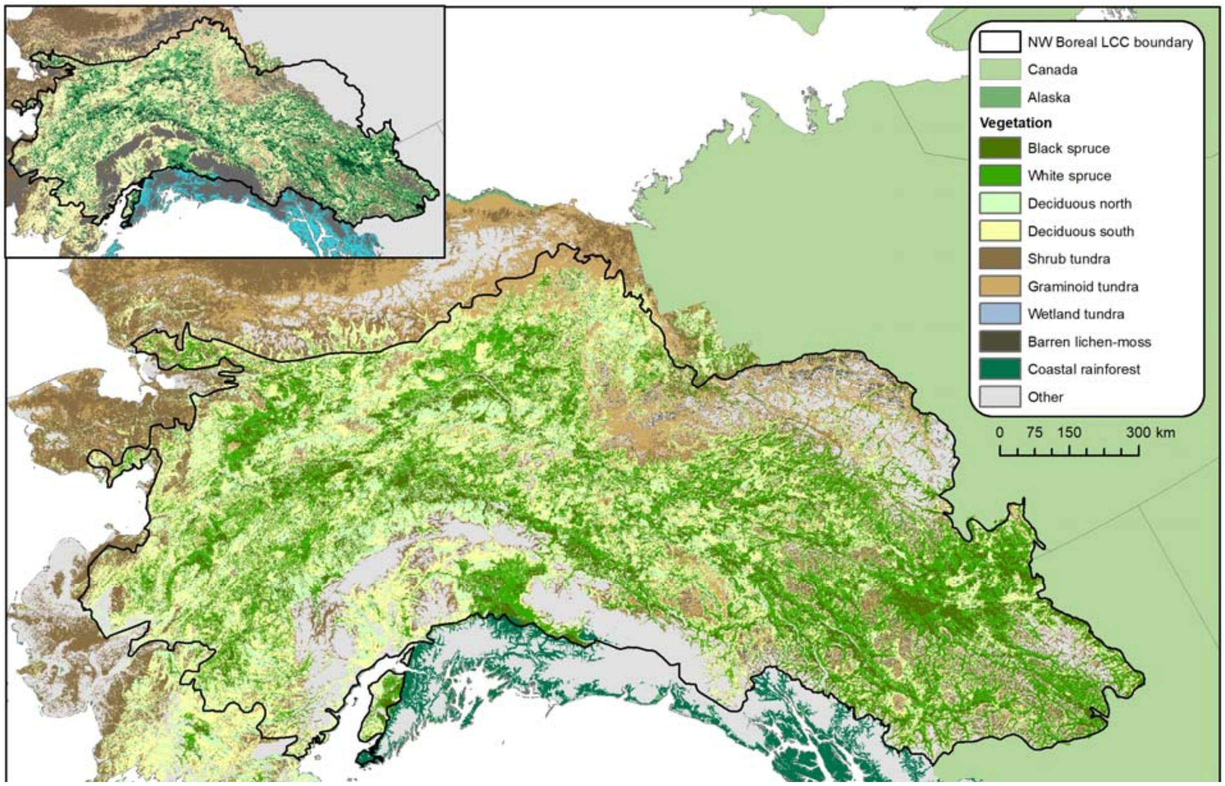


Figure 3. Distribution of vegetation classes in the NWBLCC planning region used to identify MDRs. Inset map shows the spatial extent of the original SNAP (2015a) Land Cover v2.0 which does not include the Northwest Territories in the north-east section of NWBLCC boundary.

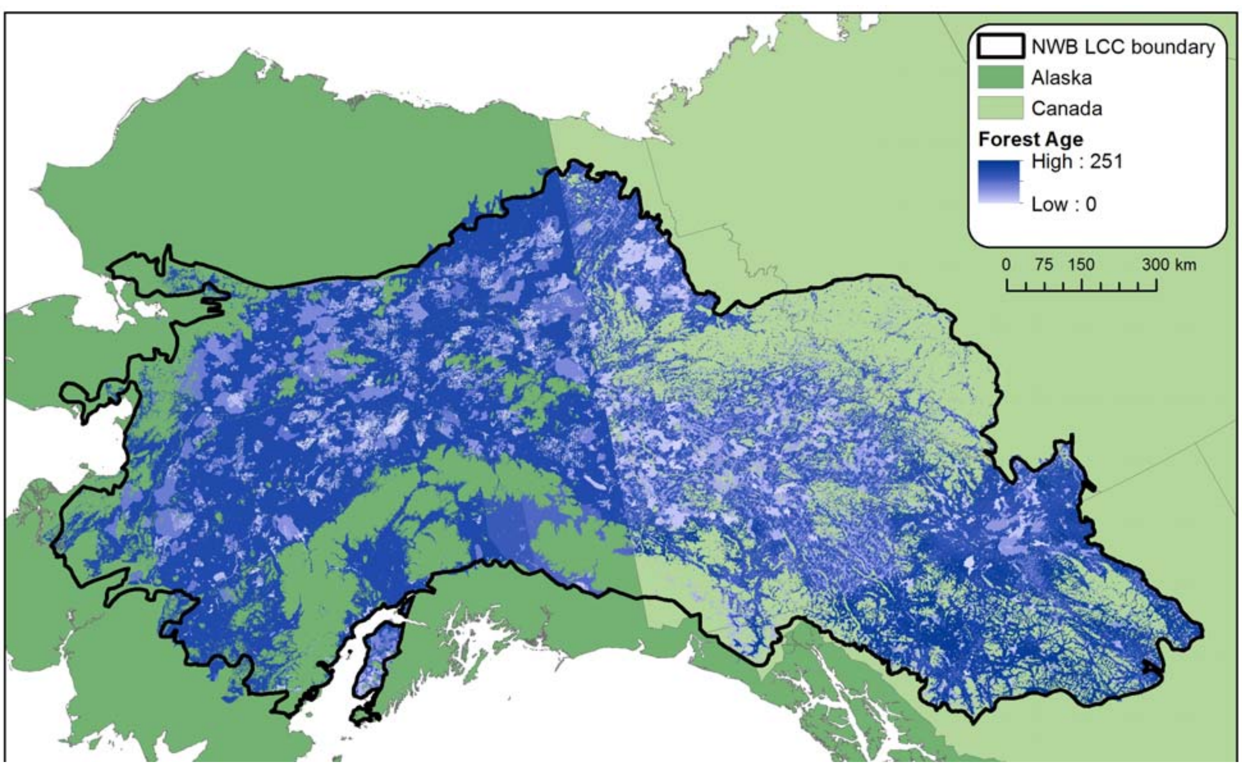


Figure 4. Forest age map (Pan *et al.* 2011) updated to 2011.

Fires

We used fire history data from the Alaska Large Fire database (Table 2) and the Canadian National Fire Database (Table 3) to create a complete fire history dataset for the study area, spanning 1940-2014 (Figure 5). This dataset is comprised of points. Fire polygon data were not used because polygon data were not available for all fires in Canada. Only lightning ignited fires were used in the analysis.

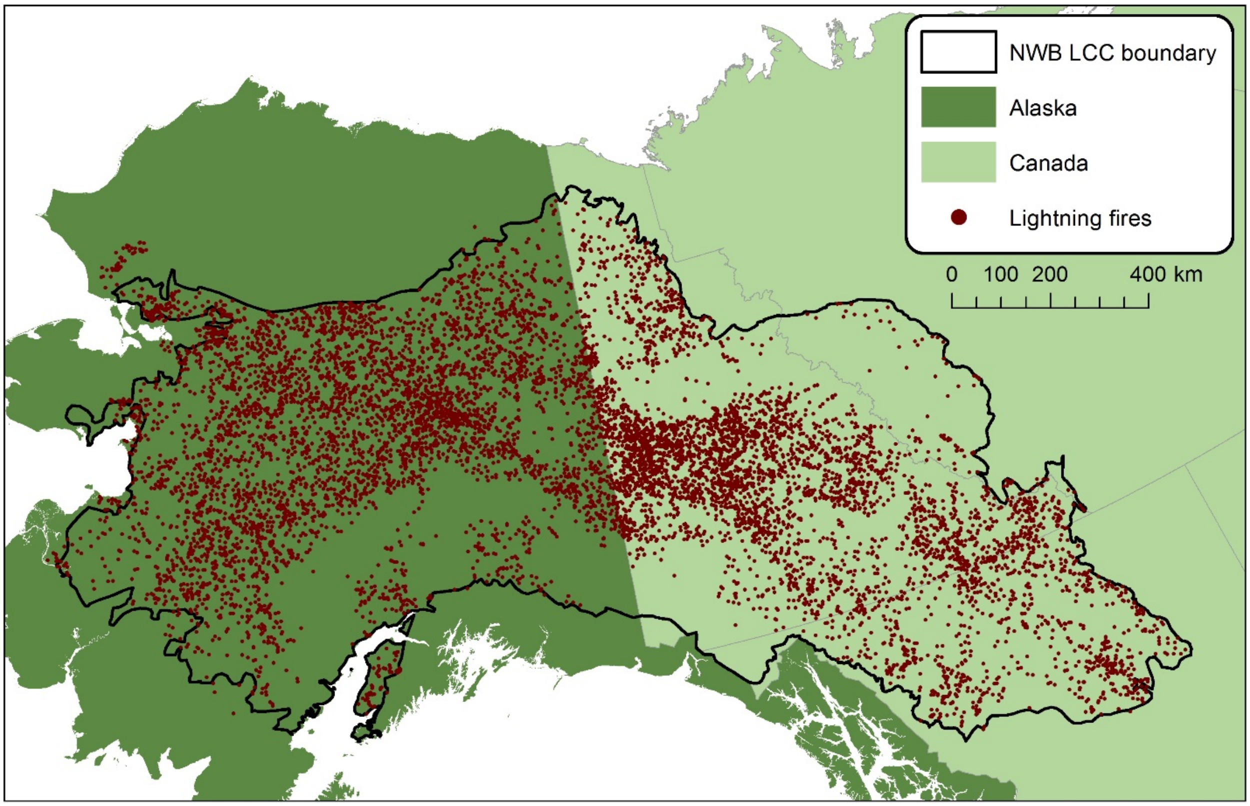


Figure 5. Distribution of lightning caused fires from 1940-2014.

MDR Analysis

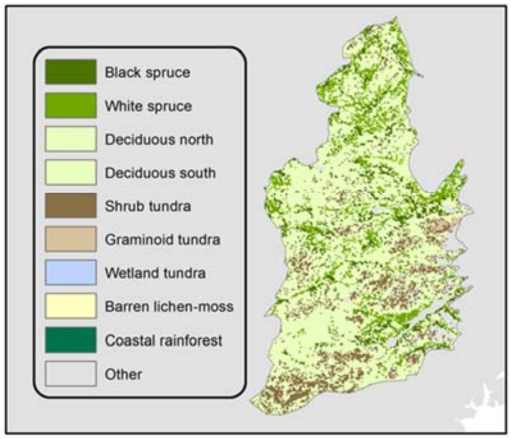
MDR sizes are estimated with the intent to maintain natural disturbance regimes such as fire and minimum amounts of flammable vegetation types. The core of the MDR analysis consists of a search for a minimum candidate reserve within each ecoregion that meets the minimum area requirements for each flammable vegetation type. Minimum area requirements for each flammable vegetation type are calculated using methods described in Leroux *et al*. (2007). We identified five flammable vegetation types for identifying MDRs: black spruce, white spruce, north-facing deciduous, south-facing deciduous, and shrub tundra, and in four ecoregions, a sixth vegetation type: graminoid tundra. For each ecoregion, we estimated the minimum size of a MDR (M) using the regional abundance of flammable vegetation types and the estimated maximum fire size (EMFS). EMFS is the largest fire expected to occur in an ecoregion based on the historic distribution of fire sizes. The calculation of M for the Lime Hills ecoregion is illustrated in Figure 6. First, we calculated the ratio of each flammable vegetation class (a_i) relative to the most abundant vegetation class (*i.e.*, a_i /11877). These ratios were then multiplied by the EMFS to calculate y_i. The y_i values are the minimum amount of each flammable vegetation type that must occur within an MDR, and as such are the targets used to identify the candidate MDR in the moving window analysis. The minimum size of an MDR is the sum of the y_i values, which we refer to as M.

The regional EMFS is assigned to the most abundant vegetation type e.g. deciduous (south)

Area of each veg type in the ecoregion

Veg class	a_i (km²)
Black spruce	1995
White spruce	3177
Deciduous (north)	6756
Deciduous (south)	11877
Shrub tundra	3095

a_i = area of the i^{th} vegetation class



Area of each veg type is rescaled to the regional EMFS

Veg class	y_i (km²)
Black spruce	166
White spruce	264
Deciduous (north)	561
Deciduous (south)	986
Shrub tundra	257

1. Calculate min area of each veg class: $Yi = EMFS \times a_i / a_{max}$

2. Calculate minimum reserve area: $M = sum(y_i) = 620$ km²

Figure 6. Estimating the minimum size of an MDR. The minimum MDR size is estimated from the areas of the five flammable vegetation types in the planning region (a_i). These areas are divided by the area of the most common class (a_i/11877), in this case Black spruce, and then multiplied by the EMFS value to get vegetation specific targets. The resulting target values for each vegetation type are represented by the y_i values. The sum of the y_i values is the M-value: the minimum size for an MDR.

We used a GIS moving window to search for MDR solutions, starting with a minimum window size equal to M. A square window was moved through all possible positions in the reference area and searched for the y_i targets identified in Figure 6. If the targets were not met following the examination of all possible solutions of a given window size, the size of the window was increased by one pixel on all four sides. This process was repeated until a window was found that achieved all vegetation area targets. This solution window became the **candidate MDR** and was tested for long-term vegetation resilience in CONSERV.

MDR size can be inflated in cases where one of the flammable vegetation types is rare on the landscape. Therefore, we present two sets of results for each ecoregion: one using all flammable vegetation classes as targets (black spruce, white spruce, deciduous north, deciduous south, shrub tundra), and another where rare vegetation classes (defined as <5% of total flammable area) were removed from the analysis.

Graminoid Tundra Ecoregions

Four ecoregions in the northern regions of the NWBLCC study region are dominated by graminoid tundra vegetation (Figure 7). In the boreal, we do not usually include grassland vegetation types as targets for representation because grassland fires are not dominant features of the fire regime, and grassland vegetation types are often rare on the landscape. This rarity can cause inflated MDR values during the moving window analysis, which is undesirable especially where grassland fires play a small role in the fire regime. However, in the four northern ecoregions shown in Figure 7, graminoid tundra is a dominant vegetation type, often being the most abundant land class in the ecoregion. For these ecoregions, tundra fires in graminoid areas make up a significant portion of the area burned in the historic fire record. For these ecoregions, we added graminoid tundra as a target in the MDR analysis (*i.e.*, an a_i value in Figure 6), and we present results for both the original 5-class analysis and the 6-class analysis that included graminoid tundra.

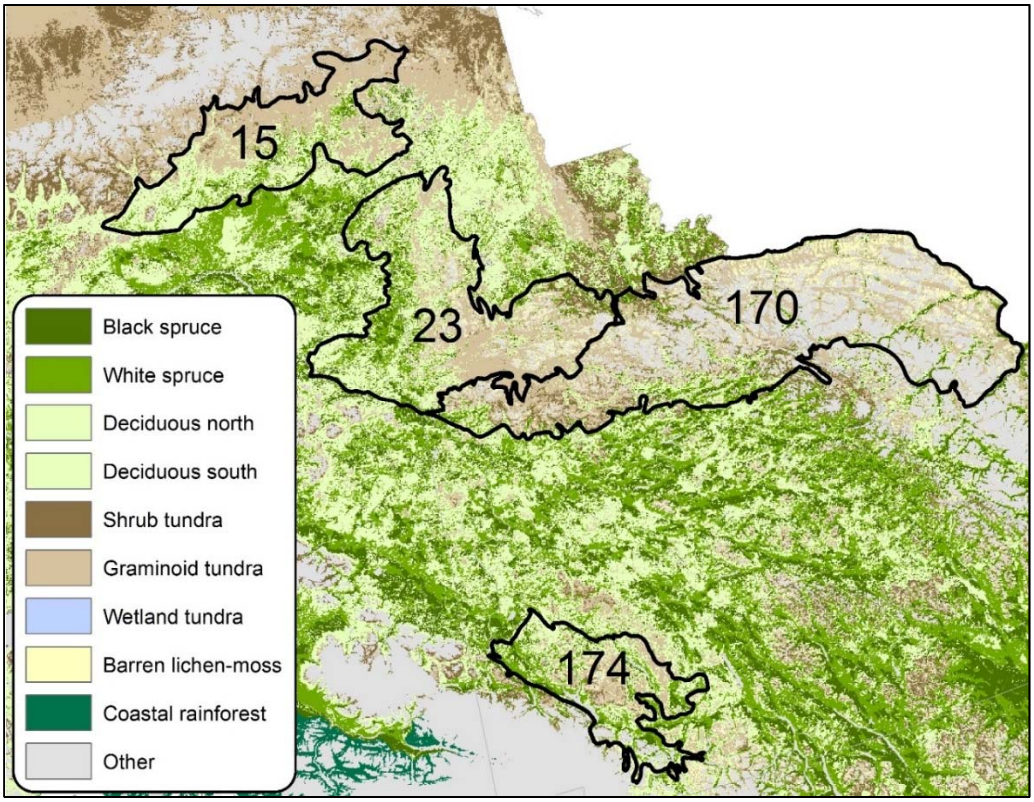


Figure 7. In ecoregions 15, 23, 170, and 174, graminoid tundra was the most abundant vegetation class, comprising 20-44% of the total flammable vegetation cover. These ecoregions were analyzed using a graminoid tundra as a sixth vegetation target. Results are presented with and without this additional target for ecoregions 15, 23, 23a, 23b, 170, and 174.

CONSERV Simulations

The final step in estimating MDR size is to evaluate the resilience of the candidate MDR to fire (*i.e.*, ability to maintain flammable vegetation types). This is done using CONSERV, a dynamic landscape simulation model that simulates fire and forest succession at large spatial and temporal scales. For this analysis, candidate MDRs were evaluated using a simulation run of 250 years, replicated 100 times. During the simulation, the area of each vegetation type was tracked yearly. To be resilient, the area of each vegetation class must stay above a user-defined threshold. For this analysis, we used 1 km^2. Candidate MDRs that maintained a minimum 1-km^2 all flammable vegetation types throughout the simulation were considered resilient and the MDR value assigned to the ecoregion.

In addition to the vegetation and age layers for the planning region described above, CONSERV requires fire parameters and a vegetation succession matrix.

Fire Parameters

For each ecoregion, we used fire history data to estimate four fire parameters: estimated maximum fire size (EMFS), probability of ignition (Pi), probability of escape (Pe), and probability of spread (Ps). For EMFS estimations, we used all fires larger than 1ha from 1940-2014 to maximize sample size. EMFS was estimated by fitting the available data to a truncated Pareto distribution and identifying the largest expected fire size from the distribution curve (Cumming 2001). If sample sizes were too small for this approach, we used an alternative method where EMFS was approximated as 1.3 times the observed maximum fire size. This multiplier was estimated from the correlation between observed maximum fire sizes and EMFS values for Canadian boreal ecoregions based on lightning-based ignitions and a truncated Pareto distribution. For the other three fire parameters, we used all fires from 1985 onwards because these are the most reliable estimates available. If sample sizes for a given ecoregion were too small, we included fires from 1940 onwards.

Forest Succession

We developed a succession matrix (Table 4) based on the succession pathways used by the ALFRESCO model in the boreal forest of Alaska (Figure 8, Rupp *et al*. 2000, 2001, 2002). Deciduous forests can proceed along two different pathways depending on whether they are north- or south-facing (simplification of rules used by Rupp et al. 2002). Consequently, we split the deciduous class into north- and south-facing deciduous classes. The succession matrix was reviewed by Jill Johnstone (University of Saskatchewan) to ensure it reflected the basic rules in ALFRESCO and was suitable for modelling the region. While we did not use graminoid tundra as a target class for most MDR analyses, it was included as a flammable class in the matrix as a facilitator of fire spread.

Table 1. Succession matrix for NWBLCC in Alaska. Each pixel is assigned to a trajectory during initialization and stays in that trajectory for the rest of the simulation. Fire resets the age of a pixel to zero. Natural death resets the age of a pixel to 3.

Type	Prob	0-2	3-40	41-80	81-120	121+
Black spruce	1	Burned	Deciduous NA	Black spruce	Black spruce	Black spruce
White spruce	1	Burned	Deciduous SA	Deciduous SA	White spruce	White spruce
Deciduous NA[1]	1	Burned	Deciduous NA	Black spruce	Black spruce	Black spruce
Deciduous SA[2]	1	Burned	Deciduous SA	Deciduous SA	White spruce	White spruce
Shrub tundra	1	Burned	Shrub tundra	Shrub tundra	Shrub tundra	Shrub tundra
Graminoid tundra	1	Burned	Graminoid tundra	Graminoid tundra	Graminoid tundra	Graminoid tundra
Burned[3]	1	Burned	Burned	Burned	Burned	Burned

[1] Deciduous NA - north facing (aspect) cell more likely to succeed to black spruce.
[2] Deciduous SA - south facing (aspect) cell more likely to succeed to white spruce.
[3] Burned - Does not occur in initial map and thus actual trajectory is irrelevant.

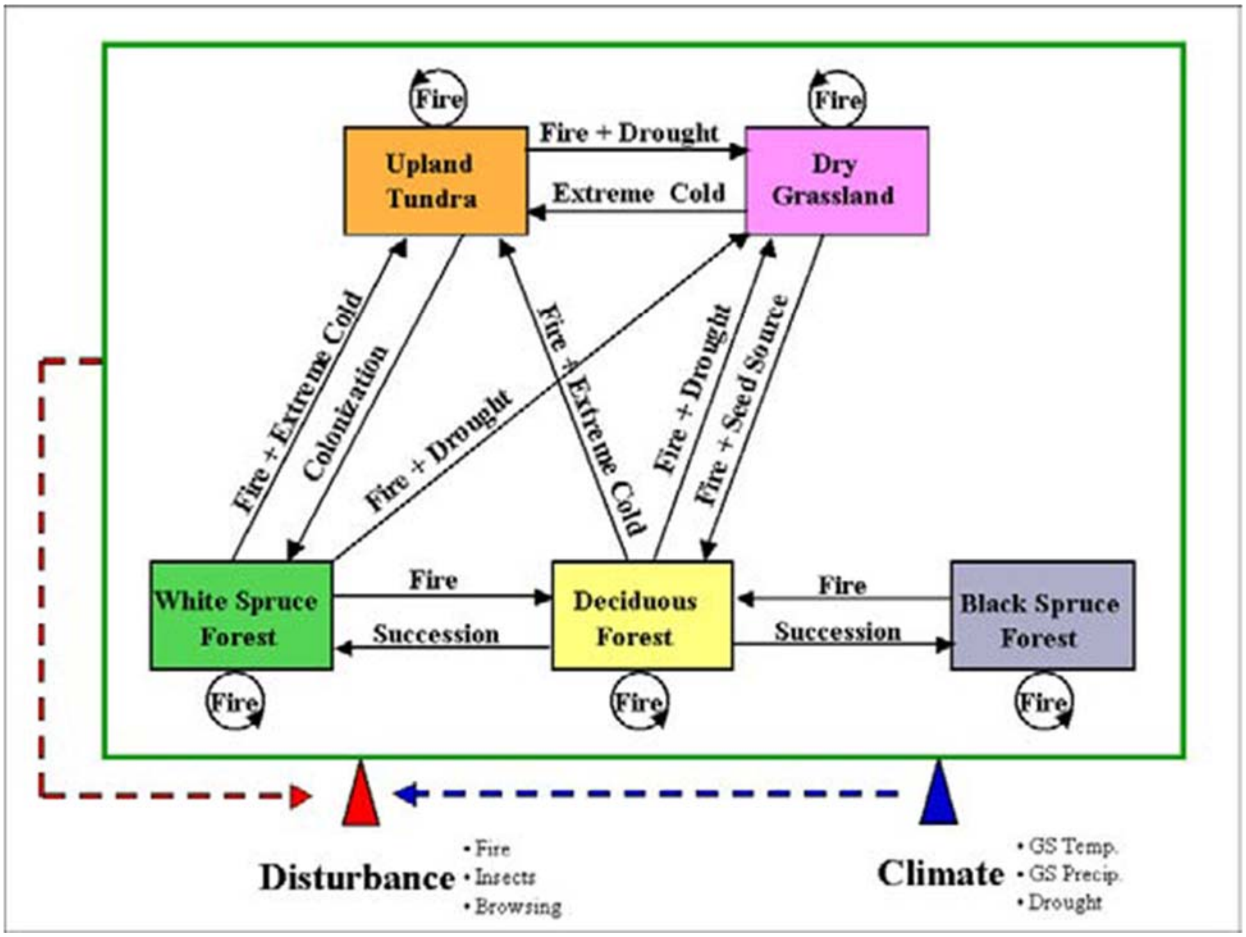


Figure 8. Succession pathways used by the ALFRESCO model in the boreal forest of Alaska (Rupp *et al.* 2000 and 2002). Image from https://www.snap.uaf.edu/sites/default/files/ALFRESCO_overview.pdf. CONSERV does not model climate change, so when developing the succession matrix for the MDR analysis, climate change pathways (*e.g.*, “fire + extreme cold” and “fire + drought”) were not considered.

RESULTS

Fire Parameters

Fire parameters were estimated for all ecoregions, except 12, 17, and 28. The number of fires used for parameter estimation ranged from 27 to 1,180 (Table 5). EMFS values ranged from 138 km^2 in the Cook Inlet Basin ecoregion to 5,674 km^2 in the Nulato Hills ecoregion (Figure 9). The EMFS value for ecoregion 13 was calculated using the function 1.3 times maximum observed fire. Fire parameters were not calculated for ecoregions 12, 17, and 28. Ecoregion 12 did not have any fires. Ecoregions 17 and 28 had too few fires (<10) to support reliable estimates of fire parameters. Ecoregions 12, 17, and 28 have high levels of protection, ranging from 88-100% protection (Appendix 3).

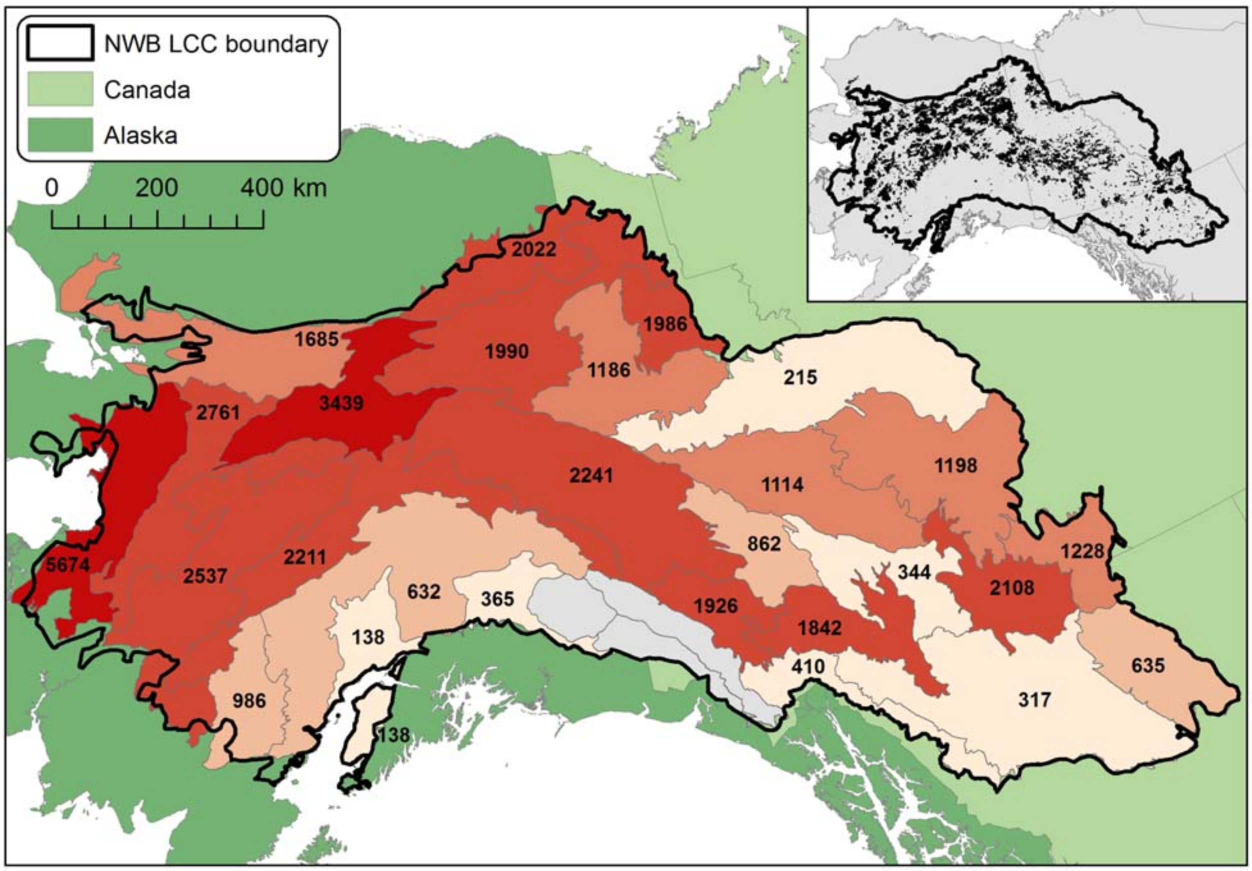


Figure 9. Estimated maximum fire sizes (EMFS) in km^2. Inset map shows available fire polygons from 1940-2014. Grey ecoregions (12, 17, and 28) have no or too few fires to support reliable estimates of fire parameters.

Table 2. Fire parameters for ecoregions within the NWB LCC study region. See Table 1 for ecoregion names. All area values are in km^2.

Parameter	**3**	**13**	**14**	**15**	**17**	**18**
Study area (km^2)	103327	29027	19137	33731	20923	55128
Lake area (km^2)	1613	1372	1214	444	324	1644
Flammable area (km^2)	101714	27656	17923	33287	20599	53484
Range of years	1982-2013	1990-2013	1944-2013	1982-2013	1982-2013	1981-2014
Number of fires	75	133	84	86	8	493
Mean fire size (km^2)	11	2	8	45	3	23
Largest fire (km^2)	409	106	228	1635	18	1620
Range of years (EMFS)	1944-2013	1946-2010	1944-2013	1946-2013	n.a.	1939-2014
Number of fires (EMFS)	59	34	51	89	n.a.	531
Largest fire (EMFS)	409	106	228	1635	n.a.	1620
EMFS 1.3 ratio (km^2)	532	138	297	2125	n.a.	2105
EMFS estimated (km^2)	632	226	365	2022	n.a.	1685
Ignition probability	0.00002	0.00020	0.00007	0.00008	n.a.	0.00027
Escape probability	0.23	0.07	0.21	0.41	n.a.	0.35
Spread probability	0.23	0.23	0.23	0.24	n.a.	0.23

Parameter	**21**	**22**	**23**	**23a**	**23b**	**24**
Study area (km^2)	85354	28713	52160	40879.4	11242.6	58127
Lake area (km^2)	488	962	60	58.5	1.3	485
Flammable area (km^2)	84866	27752	52100	40820.9	11241.3	57643
Range of years	1981-2014	1981-2014	1982-2014	1982-2014	1957-2012	1985-2014
Number of fires	548	75	256	206	62	191
Mean fire size (km^2)	37	23	28	33.8	9.1	6
Largest fire (km^2)	2456	817	1121	1121.2	99.1	213
Range of years (EMFS)	1941-2014	1951-2014	1946-2014	1946-2014	1957-2012	1943-2014
Number of fires (EMFS)	605	79	306	246	48	221
Largest fire (EMFS)	2456	817	1121	1121.2	99.1	4699
EMFS 1.3 ratio (km^2)	3193	1062	1458	1457.5	128.8	6109
EMFS estimated (km^2)	2537	986	1186	1201.1	114.4	5674
Ignition probability	0.00019	0.00008	0.00015	0.00015	0.000098	0.00011
Escape probability	0.43	0.37	0.49	0.49	0.55	0.29
Spread probability	0.24	0.23	0.23	0.23	0.23	0.23

Parameter	**25**	**27**	**28**	**29**	**31**	**32**
Study area (km^2)	51239	64011	14314	51726	72731	102489
Lake area (km^2)	463	2298	204	3533	3703	906
Flammable area (km^2)	50776	61713	14109	48193	69028	101583
Range of years	1981-2014	1981-2014	2004-2011	1981-2014	1980-2014	1980-2014
Number of fires	457	523	4	319	417	1180
Mean fire size (km^2)	43	33	1	37	56	23

Largest fire (km^2)	2190	2093	5	1481	1879	2176
Range of years (EMFS)	1941-2014	1943-2014	n.a.	1943-2014	1943-2014	1940-2014
Number of fires (EMFS)	484	419	n.a.	355	398	929
Largest fire (EMFS)	3252	2093	n.a.	2608	1907	2176
EMFS 1.3 ratio (km^2)	4227	2720	n.a.	3390	2478	2828
EMFS estimated (km^2)	3439	2211	n.a.	2761	1990	2241
Ignition probability	0.00026	0.00025	n.a.	0.00019	0.00017	0.00033
Escape probability	0.38	0.30	n.a.	0.35	0.39	0.30
Spread probability	0.24	0.24	n.a.	0.24	0.24	0.24

Parameter	**169**	**170**	**171**	**174**	**175**	**176**
Study area (km^2)	20540	87067	72426	22867	26986	57428
Lake area (km^2)	87	81	286	1047	650	1269
Flammable area (km^2)	20453	86986	72140	21821	26336	56159
Range of years	1980-2012	1982-2012	1980-2012	1956-2011	1980-2012	1980-2012
Number of fires	119	104	121	31	300	636
Mean fire size (km^2)	51	11	19	76	24	17
Largest fire (km^2)	1760	130	231	1048	804	783
Range of years (EMFS)	1959-2012	1957-2012	1952-2012	1956-2010	1946-2012	1951-2012
Number of fires (EMFS)	142	129	157	19	211	636
Largest fire (EMFS)	1760	199	1076	1048	804	1078
EMFS 1.3 ratio (km^2)	2288	259	1398	1363	1045	1401
EMFS estimated (km^2)	1986	215	1198	1926	862	1114
Ignition probability	0.00018	0.00004	0.00005	0.00003	0.00035	0.00034
Escape probability	0.51	0.52	0.46	0.39	0.23	0.33
Spread probability	0.24	0.23	0.23	0.24	0.24	0.23

Parameter	**177**	**178**	**179**	**180**	**181**	**182**	**183**
Study area (km^2)	35868	35526	24849	105582	34466	26076	37830
Lake area (km^2)	1617	202	703	2196	1112	161	115
Flammable area (km^2)	34251	35324	24146	103387	33354	25915	37715
Range of years	1980-2012	1982-2011	1954-2012	1980-2012	1980-2012	1980-2013	1980-
Number of fires	171	76	57	300	296	135	2012
Mean fire size (km^2)	4	11	16	6	26	16	119
Largest fire (km^2)	183	155	280	300	1827	217	4
Range of years (EMFS)	1950-2012	1951-2011	1957-2010	1950-2012	1951-2012	1958-2012	201
Number of fires (EMFS)	95	79	30	209	208	146	1958-
Largest fire (EMFS)	1261	289	280	300	1827	1103	2012
EMFS 1.3 ratio (km^2)	1639	376	364	390	2375	1434	112
EMFS estimated (km^2)	1842	344	410	317	2108	1228	474
Ignition probability	0.00015	0.00007	0.00004	0.00009	0.00027	0.00015	616
Escape probability	0.15	0.34	0.28	0.24	0.22	0.43	635
Spread probability	0.23	0.23	0.23	0.23	0.24	0.23	0.00010

MDR Estimates

MDR values range from 594 km^2 to 18,159 km^2 when all vegetation classes were included (Table 6, Figure 10). Rare flammable vegetation classes occur in 14 ecoregions. When these rare classes were removed from the analysis, the MDR values for these ecoregions decreased by 0.4% to 43% (Table 6, Figure 11). The addition of the graminoid tundra target to ecoregions 15, 23, 170 and 174, further decreased the MDR estimate, with the exception of ecoregion 23 and its sub-region 23a (Table 7).

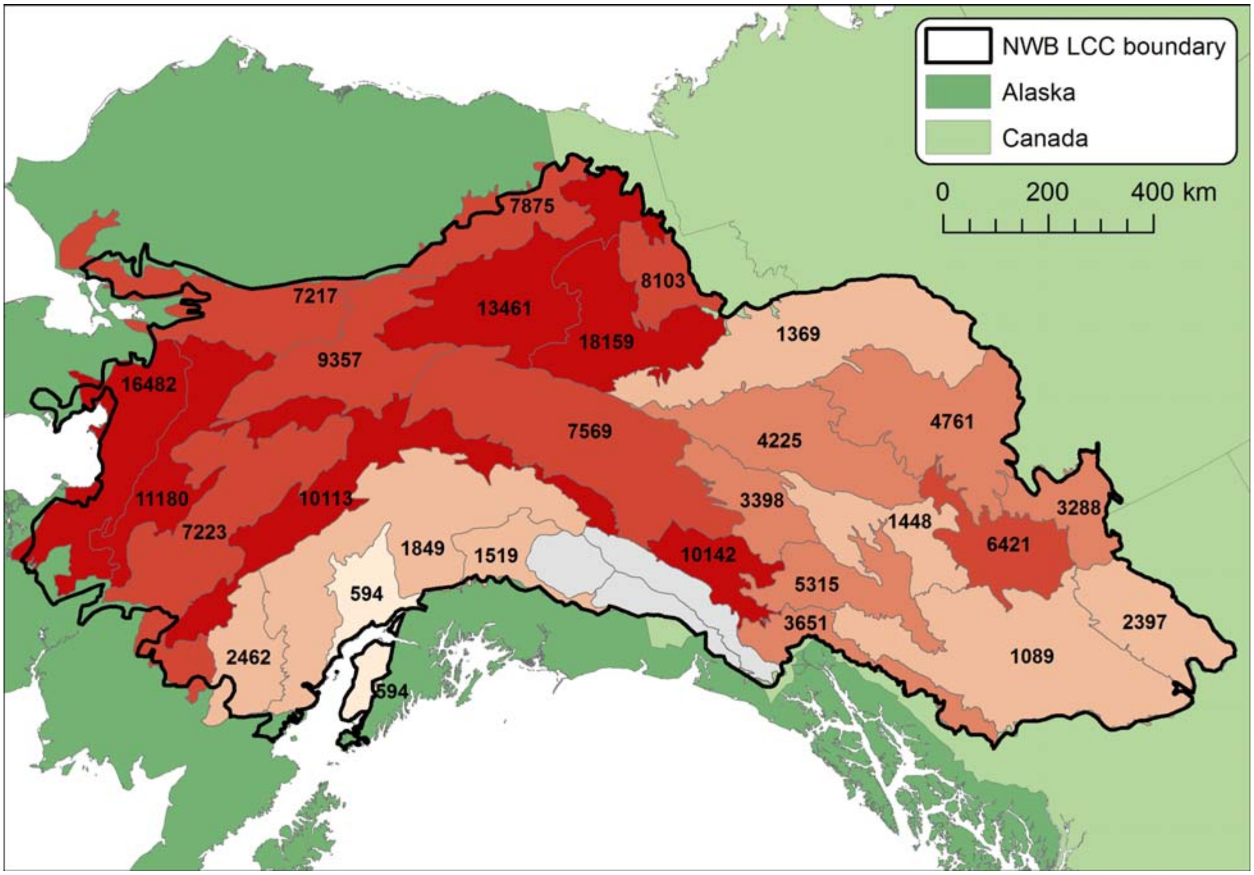


Figure 10. MDRs (km^2) estimated for ecoregions in the NWBLCC with rare classes included (Table 6).

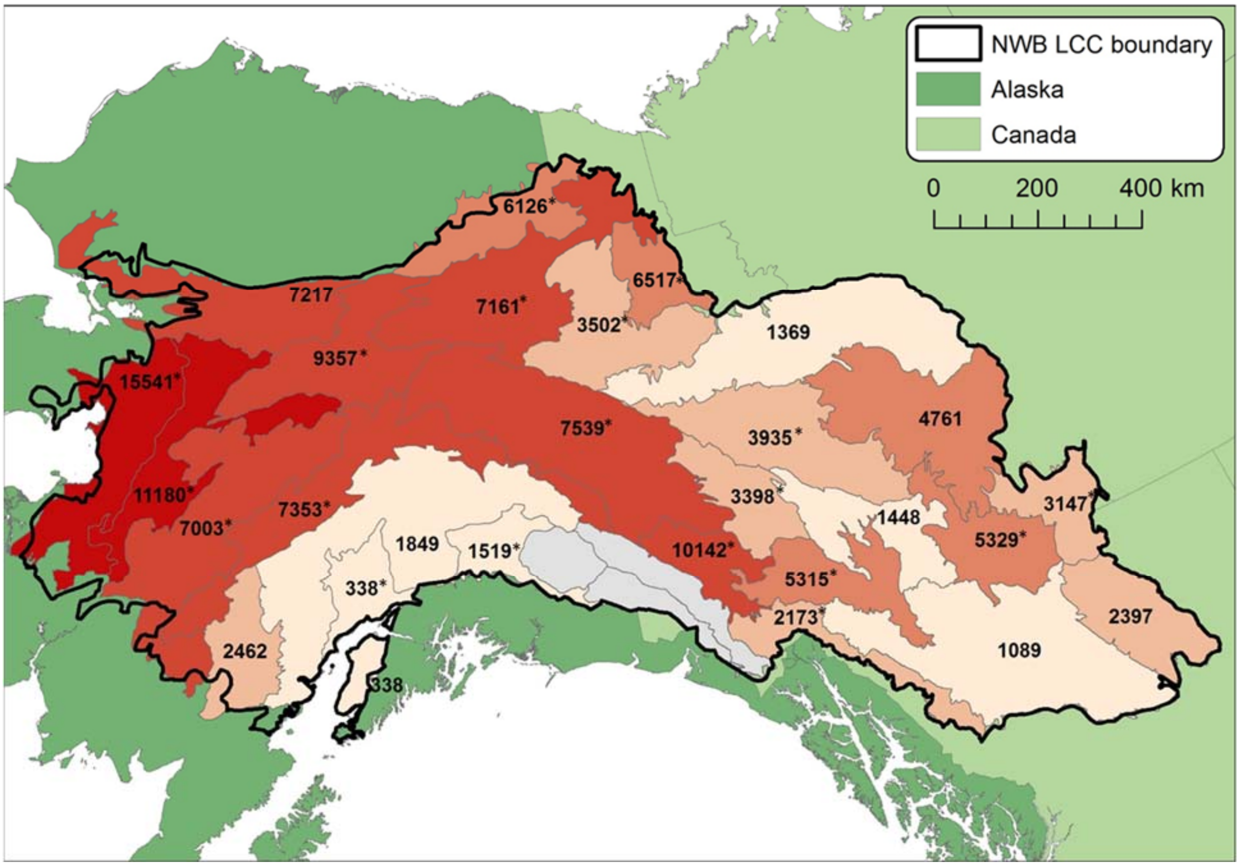


Figure 11. MDR (km^2) estimates for ecoregions in the NWBLCC decreased when targets for rare vegetation classes (*i.e.*, < 5% of the total flammable vegetation) were removed from the analysis (Table 6). Ecoregions with rare classes (N=14) are identified with an asterisk (*).

Table 6. MDR results for analysis with rare vegetation classes included, and rare vegetation classes removed. Veg1 to Veg5 are the target values for each vegetation class (Veg1: Black spruce, Veg2: White spruce, Veg3: Deciduous North, Veg4: Deciduous south, Veg5: Shrub tundra), M is the sum of these targets, MDR is the final MDR value that passed the CONSERV test, and Multi (or multiplier) is the MDR divided by the EMFS. Red values indicate vegetation targets for rare vegetation classes (*i.e.*, < 5% of the total flammable vegetation) and were removed for the 'rare classes removed' analysis.

Region	Veg1	Veg2	Veg3	Veg4	Veg5	EMFS	Rare classes included			Rare classes removed		
							M	MDR	Multi	M	MDR	Multi
3	85	112	428	632	342	632	1599	1849	2.9	1599	1849	2.9
13	26	38	64	138	3	138	269	594	4.3	266	338	2.4
14	218	365	58	74	0	365	715	1519	4.2	715	1519	4.2
15	276	645	952	2022	124	2022	4019	7875	3.9	3895	6126	3
18	653	1074	1093	1685	1239	1685	5744	7217	4.3	5744	7217	4.3
21	976	1491	1640	2537	212	2537	6856	7223	2.8	6644	7003	2.8
22	166	264	561	986	257	986	2234	2462	2.5	2234	2462	2.5
23	446	698	835	1186	128	1186	3293	18159	15.3	3165	3502	3
23a	419	705	800	1201	18	1201	3143	4054	3.4	3125	3533	2.9
23b	64	50	106	87	114	114	421	719	6.3	421	719	6.3

Region	Veg1	Veg2	Veg3	Veg4	Veg5	EMFS	Rare classes included			Rare classes removed		
							M	MDR	Multi	M	MDR	Multi
24	575	1155	3032	5674	3739	5674	14175	16482	2.9	13600	15541	2.7
25	867	1333	2323	3439	348	3439	8310	9357	2.7	7962	9357	2.7
27	2045	1314	2211	1174	6	2211	6750	10113	4.6	6744	7353	3.3
29	2218	2761	1696	2265	57	2761	8997	11180	4	8940	11180	4
31	1253	1979	1313	1990	14	1990	6549	13461	6.8	6535	7161	3.6
32	1126	1720	1609	2241	63	2241	6759	7569	3.4	6696	7539	3.4
169	592	789	1870	1986	207	1986	5444	8103	4.1	5237	6517	3.3
170	118	151	108	215	152	215	744	1369	6.4	744	1369	6.4
171	750	1198	349	713	277	1198	3287	4761	4	3287	4761	4
174	1008	1862	1459	1926	215	1926	6470	10142	5.3	6255	10142	5.3
175	633	779	715	862	0	862	2989	3398	3.9	2989	3398	3.9
176	777	1114	587	994	31	1114	3503	4225	3.8	3472	3935	3.5
177	1222	1842	516	712	36	1842	4328	5315	2.9	4292	5315	2.9
178	240	344	146	177	137	344	1044	1448	4.2	1044	1448	4.2
179	270	410	199	374	66	410	1319	3651	8.9	1253	2173	5.3
180	193	317	98	136	79	317	823	1089	3.4	823	1089	3.4
181	1680	2108	419	673	12	2108	4892	6421	3	4880	5329	2.5
182	802	1228	293	550	14	1228	2887	3288	2.7	2873	3147	2.6
183	423	635	224	192	169	635	1643	2397	3.8	1643	2397	3.8

Table 7. MDR results for analysis using 6 vegetation classes, with rare vegetation classes included, and rare vegetation classes removed. Veg1 to Veg6 are the target values for each vegetation class (Veg1: Black spruce, Veg2: White spruce, Veg3: Deciduous North, Veg4: Deciduous south, Veg5: Shrub tundra, Veg6: Graminoid tundra), M is the sum of these targets, MDR is the final MDR value that passed the CONSERV test, and Multi (or multiplier) is the MDR divided by the EMFS. Red values indicate vegetation targets for rare vegetation classes (*i.e.*, < 5% of the total flammable vegetation) and were removed for the 'rare classes removed' analysis.

Region	Veg 1	Veg 2	Veg 3	Veg 4	Veg 5	Veg 6	EMF S	Rare classes included			Rare classes		
								M	MDR	Mult	M	MDR	Multi
15	169	394	581	1234	76	2022	2022	447	6065	3	4231	4925	2.4
23	324	507	606	861	93	1186	1186	357	1303	11	3484	4225	3.6
23a	394	663	752	1128	17	1201	1201	415	5041	4.2	4138	5041	4.2
23b	15	12	25	20	27	114	114	213	361	3.2	213	361	3.2
170	25	32	23	45	32	215	215	372	625	2.9	372	625	2.9
174	984	1817	1424	1880	210	1926	1926	824	9836	5.1	8241	9836	5.1

Discussion

Multiplier values (MDR/EMFS) indicate the ratio of the final MDR size relative to the EMFS and ranged from 2.5 - 15.3 across all ecoregions when rare classes were included. High multiplier values can be caused by low levels of flammable vegetation, rare target classes that are difficult for the moving window to find, or highly aggregated patterns of vegetation which require a larger search window to meet all vegetation targets. These high multipliers were all reduced by either removing rare classes from the ecoregion, or adding graminoid tundra as a sixth vegetation class. The highest multiplier after making these corrections was 5.3 in ecoregions 174 (Ruby Ranges) and 179 (Yukon-Stikine Highlands).

All MDR values reported here are based on fire as the sole disturbance type. In reality, multiple natural disturbances exist the boreal region including insect defoliators. These disturbances can interact such that an MDR based on multiple disturbance types is likely to be larger than one based on fire alone. Since landscape models do not yet allow for multiple interacting disturbance agents, we focus on fire as the dominant disturbance type and expect MDRs using fire to be the most accurate based on the disturbance regime of the region.

Future work should focus on incorporating multiple disturbance types into the CONSERV model, and predicting how those disturbances will be altered by climate change. Climate change is likely to increase the footprint of some disturbance types which could mean that MDRs need to be larger in order to remain resilient to changing disturbance regimes.

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Appendix 1. Detailed analysis steps

1. Select analysis units
    a. Use the 2001 Unified Ecoregions of Alaska and the Atlas of Canada Ecoregions to select ecoregions that intersect the NWB LCC (30 ecoregions in total). For the 5 boundary ecoregions, use the AK ecoregions since they are not clipped at the boundary.

2. Create vegetation grids
    a. Alaska. Reclassify and modify the landcover grid to create a vegetation grid that matched the succession matrix.
        i. Reclassify landcover grid (1=black spruce, 2=white spruce, 3=deciduous, 5=shrub tundra, 6=graminoid tundra, 7=wetland tundra, 8=barren lichen-moss, 9=coastal rainforest, 10=other)
        ii. Reclassify aspect map into north facing (0=300-90 degrees) and south facing (1=90-300 degrees).
        iii. Reclassify vegetation grid into a binary grid (deciduous = 3, others = 0)
        iv. Add reclassified aspect map to deciduous grid and rename class 3 to "deciduous sa" and 4 to "deciduous na"
    b. Canada. Reclassify NALC2005 to create a vegetation grid that matches the map made in 2.a. (see Appendix 2)

3. Create forest age grids
    a. Alaska. Use the latest forest age map obtained in 2011 (2006 updated to 2011).
    b. Canada. Use the 2004 forest age map and update to 2011.
        i. Use NFDB polygon data to create a binary fire grid for each year between 2004-2011.
        ii. For each year: reset "age" pixels to 0 if burned that year; increment other pixels by 1 year.

4. Generate ecoregion-level input data
    a. Extract vector maps for each ecoregion, ensuring that all datasets have the same coordinate/projection system (Albers Equal Area for Alaska) and spatial extent.
        i. Extract fire history data using all points in the ecoregion boundary.
        ii. Extract lakes/large rivers polygons by clipping to the ecoregion boundary. Re-calculate area in km^2. Lakes data is used to calculate terrestrial area used in fire parameter calculations.
    b. Extract raster maps for each ecoregion, ensuring that all datasets use the same coordinate/projection system (Albers Equal Area for Alaska) and have the same resolution, spatial extent, and grid.
        i. Create a 1 km^2 raster version of each ecoregion for use as a "template" raster.
        ii. Use the "template" raster as a mask to extract vegetation and forest age grids; convert to ASCII format for use with CONSERV.

5. Estimate fire parameters
    a. EMFS, Pi, Pe, and Ps are estimated using all 1985-2014 fire points within the ecoregion.
        i. Modify R scripts to use Alaska fire history data.
        ii. Estimate EMFS using all fires between 1985-2014 that are at least 100 ha (1 pixel) in size.
        iii. Estimate Pi, Pe, Ps using fires of all sizes occurring between 1940-2014.
6. Develop succession matrix
    a. Create a succession (transition) matrix for CONSERV using rules adapted from the ALFRESCO model and described in the literature.
    b. Send succession matrix for review (J. Johnstone, S. Cumming). Revise as necessary.
7. Search for minimum candidate reserve(s)
    a. Use the Python/ArcGIS script *movingWindow.py* to search for the smallest candidate reserve(s) that contains all flammable/successional vegetation types in their minimum amounts.
8. Evaluate resilience of candidate reserve(s)
    a. Use CONSERV to evaluate the resilience of the candidate reserves. For each ecoregion:
        i. Parameterize CONSERV using succession matrix and ecoregion specific fire parameters and input vegetation and age grids.
        ii. Add candidate reserve grid identified in the moving window analysis (step 7).
        iii. Run simulation 100 times, each for 250 years.
        iv. Evaluate the results to determine if minimum amount of each dynamic vegetation class was maintained throughout the 100 simulations.
9. Summarize results
    a. Generate summary tables for each ecoregion:
        i. fire_params_ecoregions.csv summarizes fire parameters for each ecoregion.
        ii. reserve_stats_ecoregions.csv summarizes the moving window analysis for each ecoregion

APPENDIX 2. CREATING VEGETATION GRID TO FILL IN MISSING PORTIONS OF THE ALFRESCO VEGETATION MAP.

Aim: replicate ALFRESCO methods as best as possible to fill in gaps

Input datasets:

- North American Land Cover 2005 (CEC 2013)
- Land Cover v2.0 (SNAP 2015)[1]
- National Ecological Framework of Canada (Marshall *et al.* 1999)
- Aspect map derived from PRISM DEM model[2] and Canada 3D

Step 1.
Clipped NALC 2005 map to the outline of the ecoregions making up the study region.

Step 2.
Resampled to 1km^2 using majority method and snapped to ALFRESCO Land Cover v2.0 grid.

Step 3.
Reclassified NALC 2005 classes based on ALFRESCO rules stated in the 'Research Data / Ancillary Data / Metadata / Landcover' section of the following webpage: www.snap.uaf.edu/node/102 (summarized in Table 2.1)

- This takes care of Spruce (which will later be split into bS and wS), Deciduous (which will later be split into north and south facing), Shrub Tundra, and Barren lichen-moss.
- Wetlands were assigned to the Spruce class. ALFRESCO assigns wetland to spruce bog if it is inland, and coastal wetland if it is in a coastal ecozone (Pacific Maritime in Canada). None of our missing data areas were in a coastal ecozone so they were assigned to Spruce.

Step 4.
Assign dubious classes.

- Classes 10 (Temperate or sub-polar grassland) and 12 (Sub-polar or polar grassland-lichen-moss) from NALC 2005 should be split into Graminoid Tundra or Grassland depending on growing season temperature. However, the ALFRESCO legend has no Grassland class so we assigned to all of these cells to Graminoid Tundra (value 6). This will not influence the MDR analysis because they are not flammable (*i.e.,* will not affect the moving window analysis).

[1] SNAP (Scenarios Network for Alaska and Arctic Planning) http://www.snap.uaf.edu/data.php
[2] http://ckan.snap.uaf.edu/dataset/elevation

Table 2.1. Reclassification rules.

ALFRESCO class name	Reclassified value	NALC 2005 class value
No vegetation	0	15,16,17,18,19
Spruce	1	1,2,14
Deciduous	3	5,6
Shrub tundra	5	11
Graminoid tundra	6	10,12
Barren lichen-moss	7	13
Temperate or sub-polar shrubland	8	8

Step 5.
Split Temperate or sub-polar shrubland into deciduous or shrubland tundra based on mean growing season temperature.

- ALFRESCO is split into deciduous where mean growing season temp (averaged from 1961-1990 May, June, July August avg temps) was >6.5°C, and into shrub tundra where mean growing season temp was <6.5°C.
- We replicated this using climate normal mean summer temperature (June-August) data from 1961-1990. The data were downloaded from www.ualberta.ca/~ahamann/data/climatewna.html.

Step 6.
Split Deciduous into north and south.

- Used aspect map split between north facing (0: 300 - 90 degrees) or south facing (1: 90 - 300 degrees).
- Reclassified vegetation grid into a binary grid (deciduous = 3, others = 0)
- Summed aspect map and deciduous grid with raster calculator, reclassified to keep 3 (deciduous north) and 4 (deciduous south) and set everything else to zero.
- Reclassified vegetation grid so deciduous was zero and everything else stayed the same.
- Combined new deciduous grid with other classes to get updated vegetation map.

Step 7.
Split Spruce into black and white based on north-south layer.

- Used the same north south layer as for the deciduous, Spruce class was split into black spruce if it was north facing and white if it was south facing.
- Saved final map with deciduous and spruce split as NALC_SPLIT.tif

Step 8.
Merged the NALC_SPLIT map with the primary vegetation map to fill in missing areas and renamed classes to match those used in AK (Table 2.2).

Table 2.2. Final legend for veg map covering AK and Canada portion of study region.

Description	Class
Black spruce	1
White spruce	2
Deciduous north	3
Deciduous south	4
Shrub tundra	5
Graminoid tundra	6
Wetland tundra	7
Barren lichen-moss	8
Coastal rainforest	9
Other	10

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APPENDIX 3. NWB LCC ECOREGIONS WITHOUT MDR ESTIMATES

There are three ecoregions in the NWB LCC that do not have MDR estimates (Figure 3.1):

- **Ecoregion 12** - 100% protection; MDR is not required.
- **Ecoregion 28** - 100% protection; MDR is not required.
- **Ecoregion 17** -This ecoregion is 21,175 km^2 with 88% of the ecoregion within large protected areas. All land cover classes have 62-100% protection except for shrub-lichen-moss which is a relatively rare class (6 km^2) with only 8% of its area protected (Figure 3.2, Table 3.1). The large protected areas are likely sufficient for benchmarking.

  Recommendation - Proceed without an MDR. Evaluate protected areas for focal species.

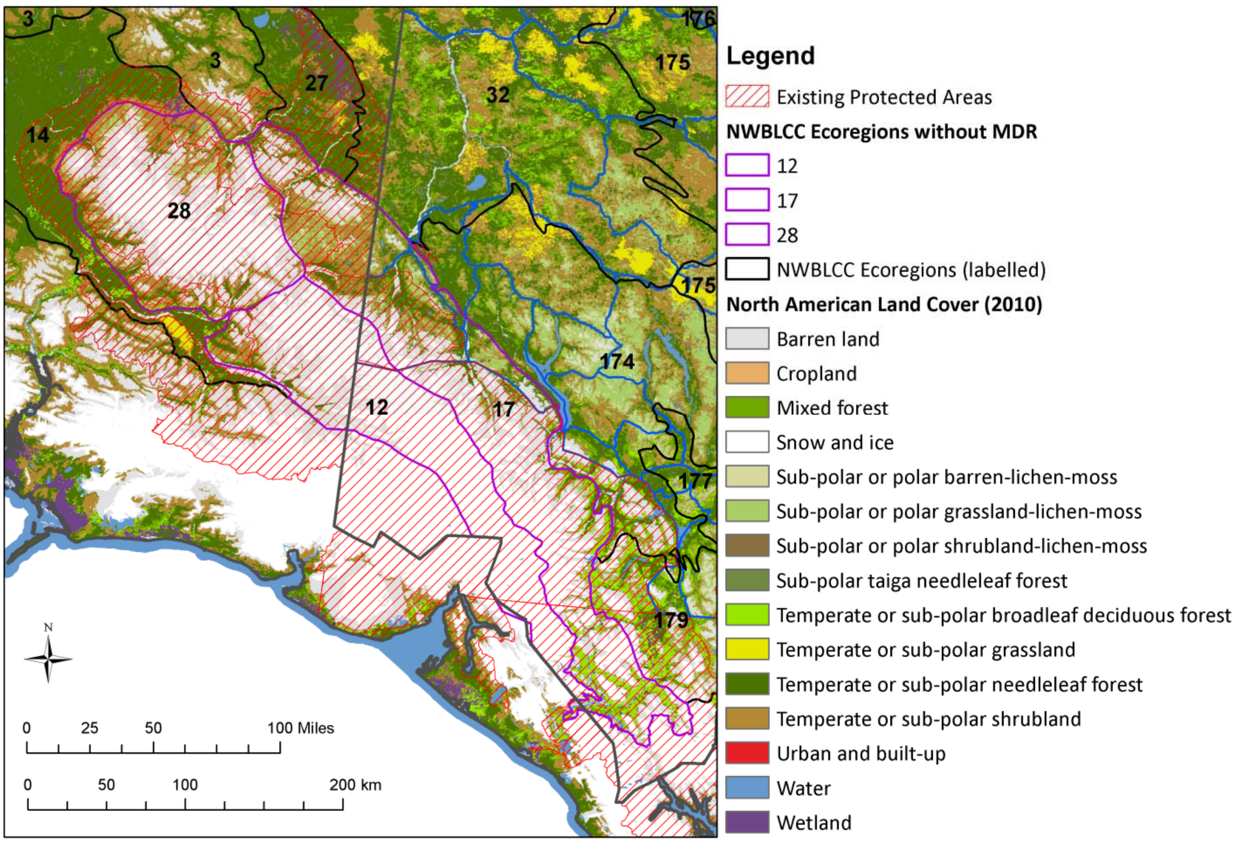

Figure 3.1. MDRs have not been estimated for ecoregions 12, 17, and 28. These three ecoregions have large amounts of protection and are dominated by barren land, snow and ice land cover classes.

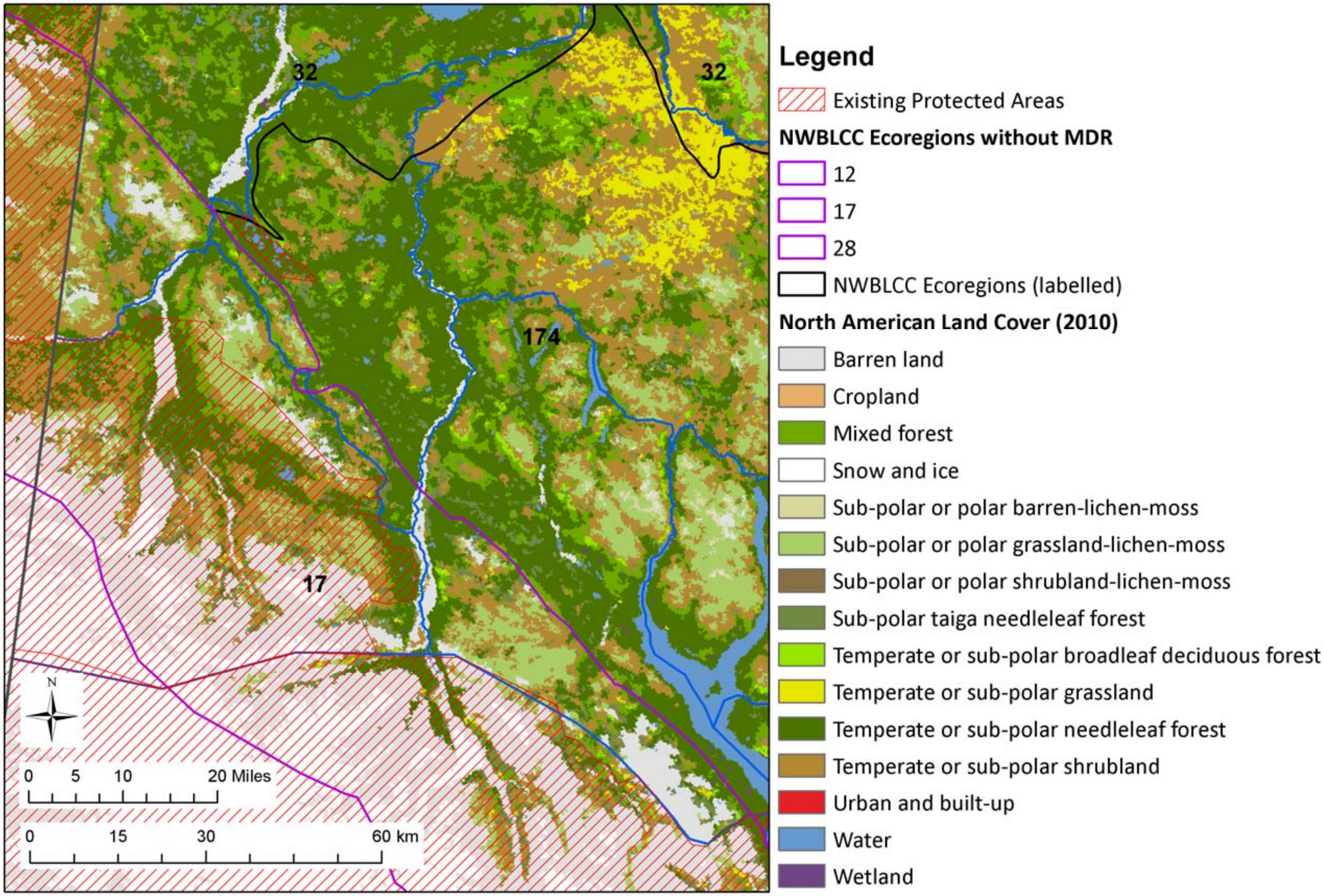

Figure 3.2. Zoom in on the unprotected region of ecoregion 17.

Table 1. Ecoregion 17 - % area of each land cover class within existing protected areas.

Land Cover Class	**Ecoregion km²**	**% Land Cover Class in PAs**
temperate or sub-polar needleleaf forest	2,061	69.0
sub-polar taiga needleleaf forest	729	66.8
temperate or sub-polar broadleaf deciduous forest	801	97.7
mixed forest	569	62.2
temperte or sub-polar shrubland	3,633	83.8
temperate or sub-polar grassland	164	93.8
sub-polar or polar shrubland-lichen-moss	6	8.6
sub-polar or polar grassland-lichen-moss	1,547	75.7
sub-polar or polar barren-lichen-moss	280	95.5
wetland	53	99.2
cropland	4	97.0
barren land	6,475	94.6
water	175	88.7
snow and ice	4,681	100.0

APPENDIX 4. ARCHIVED RESULTS.

Fire parameters and MDR results from a previous version of the analysis where EMFS was calculated using fires >100ha occurring after 1985.

Table 4.1. Fire parameters for 29 ecoregions within study region. See Table 3 for ecoregion names. All area values are in km^2. Used old fire parameters where EMFS was >1985 and >100ha.

Parameter	**3**	**13**	**14**	**15**	**17**	**18**
Study area (km2)	103326.7	29027.2	19137.2	33731	20922.7	55127.5
Lake area (km2)	1613.1	1371.6	1213.9	444	323.8	1644
Flammable area (km2)	101713.5	27655.6	17923.3	33287	20598.9	53483.5
Range of years	1990-2013	1990-2010	1944-2013	1985-2013	1991-1998	1985-2014
Total # of fires	74	133	84	84	8	483
Mean fire size (km2)	10.4	1.9	7.7	45.7	3.1	23.4
Largest fire (km2)	409.3	106.4	228.3	1634.9	18.3	1619.5
EMFS 1.3 ratio (km2)	532.1	138.4	296.8	2125.4	23.7	2105.3
# fires to est EMFS	29	19	42	62	4	306
EMFS estimated (km2)	658.3	217.9	413.4	2238.9	0	1802.4
Iginition prob	0.00003031	0.00020038	0.00006695	0.00008702	0.00001214	0.00030103
Escape prob	0.21621622	0.06766917	0.21428571	0.41666667	0.375	0.33333333
Spread prob	0.23311082	0.23082155	0.2318201	0.23675954	0.22541055	0.23479583

Parameter	21	22	23	24	25	27
Study area (km2)	85353.6	28713.4	52159.7	58127.4	51239	64011
Lake area (km2)	487.8	961.8	59.7	484.7	463.1	2297.7
Flammable area (km2)	84865.7	27751.6	52100	57642.7	50775.9	61713.4
Range of years	1985-2014	1951-2014	1985-2013	1985-2014	1985-2014	1985-2014
Total # of fires	540	99	236	191	451	517
Mean fire size (km2)	37.8	11.7	30.7	5.6	42.6	31.1
Largest fire (km2)	2456.2	223.5	1121.2	212.9	2190.3	2092.5
EMFS 1.3 ratio (km2)	3193.1	290.5	1457.5	276.8	2847.4	2720.3
# fires to est EMFS	366	72	198	115	287	250
EMFS estimated (km2)	2599.9	258.2	1240.9	256.7	2387.7	2260.8
Iginition prob	0.0002121	0.00005574	0.00015099	0.00011045	0.00029607	0.00027925
Escape prob	0.42592593	0.44444444	0.50847458	0.29319372	0.37472284	0.28820116
Spread prob	0.23582273	0.23042915	0.23412658	0.22897057	0.23692176	0.23669013

Parameter	**28**	**29**	**31**	**32**	**169**	**170**
Study area (km2)	14313.5	51726.2	72730.7	102488.9	20539.9	87067.3
Lake area (km2)	204.1	3533.2	3703.2	905.9	86.9	81.3
Flammable area (km2)	14109.4	48193	69027.5	101583	20453	86986
Range of years	2011-2011	1985-2014	1985-2014	1986-2014	1985-2012	1985-2012
Total # of fires	4	312	407	1095	103	91
Mean fire size (km2)	1.3	36.7	56.6	24.1	58.1	11.9
Largest fire (km2)	5	1480.6	1879	2175.7	1759.7	130
EMFS 1.3 ratio (km2)	6.5	1924.8	2442.7	2828.4	2287.6	169
# fires to est EMFS	1	186	235	540	83	74
EMFS estimated (km2)	623.5	1684	1996	2267.2	2080.3	0
Iginition prob	0.00003544	0.0002158	0.00019654	0.0003717	0.00017985	0.00003736
Escape prob	0.25	0.33974359	0.38083538	0.30228311	0.5631068	0.53846154
Spread prob	0.22315806	0.2367	0.23810082	0.23535539	0.23649584	0.22966687

Table 4.1 continued. Fire parameters for 29 ecoregions within study region. See Table 3 for ecoregion names. All area values are in km^2. Used old fire parameters where EMFS was >1985 and >100ha.

Parameter	**171**	**174**	**175**	**176**	**177**	**178**
Study area (km2)	72426	22867.4	26986.3	57427.9	35867.9	35526.3
Lake area (km2)	286.4	1046.7	650.1	1269	1616.9	202
Flammable area (km2)	72139.6	21820.8	26336.2	56158.9	34251	35324.3
Range of years	1986-2012	1956-2010	1986-2012	1985-2012	1988-2010	1989-2011
Total # of fires	89	31	254	501	142	67
Mean fire size (km2)	21.4	75.8	25.9	20.5	4.2	12.5
Largest fire (km2)	231.2	1048.2	803.8	783.4	183.1	154.5
EMFS 1.3 ratio (km2)	300.6	1362.7	1045	1018.4	238	200.9
# fires to est EMFS	68	17	84	263	41	39
EMFS estimated (km2)	0	1907	921.8	820.4	233.1	191
Iginition prob	0.00004569	0.00002537	0.00034445	0.00031861	0.00014807	0.00007295
Escape prob	0.52808989	0.38709677	0.20866142	0.34331337	0.16901408	0.3880597
Spread prob	0.23237476	0.23931613	0.23730299	0.23407615	0.23019627	0.23136839

Parameter	**179**	**180**	**181**	**182**	**183**
Study area (km2)	24849.3	105582.3	34465.7	26075.7	37830
Lake area (km2)	703.4	2195.5	1111.6	160.9	114.8
Flammable area (km2)	24145.9	103386.9	33354.1	25914.8	37715.1
Range of years	1957-2010	1987-2012	1985-2012	1985-2012	1987-2012
Total # of fires	57	245	244	94	64
Mean fire size (km2)	16.3	7	14.3	16.2	2.8
Largest fire (km2)	280	299.6	352.8	216.9	70
EMFS 1.3 ratio (km2)	364	389.5	458.7	281.9	91
# fires to est EMFS	24	99	90	64	23
EMFS estimated (km2)	404.9	331.4	395.7	0	134.8
Iginition prob	0.00004001	0.00008463	0.00026127	0.00012508	0.00006527
Escape prob	0.28070175	0.26938776	0.20491803	0.4893617	0.109375
Spread prob	0.23396757	0.23039677	0.23476409	0.23148214	0.2302543

Table 4.2. Results of moving window analysis. Used old fire parameters where emfs was >1985 and >100ha.

Ecoregion	veg1	veg2	veg3	veg4	veg5	emfs	m	mdr	multi
3	88	117	446	658	357	658	1666	2025	3.1
13	41	60	101	218	5	218	425	564	2.6
14	1138	1907	305	385	0	1907	3735	4712	2.5
15	306	715	1054	2239	138	2239	4452	8367	3.7
17	18	15	21	24	17	24	95	169	7.1
18	699	1149	1169	1802	1326	1802	6145	7569	4.2
21	1000	1528	1681	2600	217	2600	7026	7359	2.8
22	43	69	147	258	67	258	584	729	2.8
23	467	730	874	1241	134	1241	3446	19008	15.3
24	26	52	137	257	169	257	641	779	3
25	602	926	1613	2388	241	2388	5770	6855	2.9
27	2090	1343	2261	1200	6	2261	6900	10356	4.6
28	60	180	244	413	167	413	1064	5054	12.2
29	1353	1684	1034	1381	35	1684	5487	6702	4
31	1257	1985	1317	1996	14	1996	6569	13386	6.7
32	1139	1740	1627	2267	64	2267	6837	7891	3.5
169	620	826	1958	2080	217	2080	5701	8244	4
170	93	119	85	169	119	169	585	1089	6.4
171	188	301	88	179	70	301	826	1089	3.6
174	998	1843	1444	1907	213	1907	6405	9923	5.2
175	676	833	765	922	1	922	3197	4545	4.9
176	573	820	432	732	23	820	2580	2926	3.6
177	155	233	65	90	5	233	548	725	3.1
178	133	191	81	98	76	191	579	755	4
179	267	405	196	369	66	405	1303	3651	9
180	202	331	103	142	83	331	861	1186	3.6
181	315	396	79	126	2	396	918	1165	2.9
182	184	282	67	126	3	282	662	931	3.3
183	90	135	48	41	36	135	350	505	3.7

APPENDIX 5. ALTERNATIVE FIRE SAMPLING METHODS.

Objective: To evaluate the effects of ecoregion-level fire sampling methods on fire parameter estimates.

Current methods for calculating fire parameters for MDR analysis use the fire point datasets from Alaska and Canada, respectively. These points were clipped to each ecoregion creating the sample of fires that were used for parameter calculations in each ecoregion. Fire points represent the ignition points of fires and, in some cases, using this method will miss fires that burned into the ecoregion. Fires that ignited outside the ecoregion but burned into the ecoregion and had a significant proportion of their area inside the ecoregion, should be included in the ecoregions fire sample because they represent realized burn events that occurred within the ecoregion.

In addition to the point data, both Alaska and Canada have polygon records where fire boundaries have been mapped. These polygon datasets are incomplete (*i.e.*, not every point has a polygon) but since most of the large fires are mapped this information could be used to supplement the point datasets and identify fires that ignited outside the ecoregion but burned into it.

Currently, only the Alaska fire data has matching fire IDs for the point and polygon data. Matching IDs are necessary so that duplicate fires can be removed once the polygon and point datasets have been merged. Fire IDs match for some areas of Canada but errors are more common and fire ID standards differ by province, and in some cases between agencies within a province. For this evaluation, we restricted the analysis to ecoregions that fall completely within Alaska.

Data were prepared in the genFirePointPoly.py script and datasets for each scenario were merged and fire parameters computed in the combinedPolyPoint_fireParams.R script.

Fire parameters were compared for four different scenarios:

1. Points only.
   This is the method currently being used where the point data is simply clipped to the ecoregion.
2. Points + intersecting polygons.
   The clipped points are supplemented with all polygons that overlap any part of the ecoregion. In the case of duplicates where a fire is represented by both a point and a polygon, the point values were kept and polygons deleted. This means that any fire that ignited inside the ecoregion maintains its full size in the sample, even if it burned out of the ecoregion.
3. Points + intersecting polygons clipped to ecoregion.
   This is the same as scenario 2, but the overlapping polygons were clipped to the ecoregion boundary, so for fires that burned into the ecoregion, only the portion of the fire that actually burned inside the ecoregion was included in the fire sample.
4. Points + intersecting polygons clipped to ecoregion + complete polygons for fires with >50% of their area in the ecoregion. This scenario combined scenarios 2 and 3. Fires were clipped to the ecoregion, unless 50% or more of their total area burned within the ecoregion, in which case their full area was included.

Results

Table 5.1. Results for the above 4 scenarios

Scenario 1	**3**	**13**	**14**	**18**	**21**	**22**	**24**	**25**	**27**	**28**	**29**
Range of years (EMFS)	1944-2013	1946-2010	1944-2013	1939-2014	1941-2014	1951-2014	1943-2014	1941-2014	1943-2014	2004-2011	1943-2014
Number of fires (EMFS)	59	34	51	531	605	78	221	484	419	2	355
Largest fire (EMFS)	409.3	106.4	228.3	1619.5	2456.2	223.5	4699.2	3251.5	2092.5	5	2607.7
EMFS 1.3 ratio (km2)	532.1	138.4	296.8	2105.3	3193.1	290.5	6109	4227	2720.3	6.5	3390
EMFS estimated (km2)	631.6	225.5	364.6	1684.8	2536.7	0	5674.3	3438.6	2211.4	111.6	2761.4
Iginition prob	2.3E-05	0.0002	6.7E-05	0.000271	0.00019	5.57E-05	0.00011	0.000265	0.000249	3.54E-05	0.000195
Escape prob	0.226667	0.067669	0.214286	0.346856	0.434307	0.444444	0.293194	0.382932	0.296367	0.25	0.354232
Spread prob	0.232984	0.230822	0.23182	0.23461	0.235682	0.230429	0.228971	0.23684	0.236787	0.223158	0.236534
Method 2	**3**	**13**	**14**	**18**	**21**	**22**	**24**	**25**	**27**	**28**	**29**
Range of years (EMFS)	1944-2013	1946-2010	1944-2013	1939-2014	1941-2014	1951-2014	1943-2014	1941-2014	1943-2014	1948-2011	1943-2014
Number of fires (EMFS)	67	34	51	555	651	84	232	521	449	3	415
Largest fire (EMFS)	409.3	106.4	228.3	2487.4	2853.9	816.7	4699.2	3251.5	2092.5	56.9	4573
EMFS 1.3 ratio (km2)	532.1	138.4	296.8	3233.6	3710.1	1061.7	6109	4227	2720.3	74	5944.9
EMFS estimated (km2)	529.9	225.5	364.6	2586.6	2933.5	952.5	5532.1	3395.2	2184.8	1016.7	4779.5
Iginition prob	2.52E-05	0.0002	6.7E-05	0.000277	0.000201	8.27E-05	0.000112	0.000277	0.000261	5.54E-06	0.000217
Escape prob	0.292683	0.067669	0.214286	0.361111	0.460345	0.397436	0.32	0.40795	0.328467	0.4	0.421348
Spread prob	0.234046	0.230822	0.23182	0.234763	0.236523	0.234747	0.230231	0.237592	0.237933	0.231196	0.237067

Method 3	**3**	**13**	**14**	**18**	**21**	**22**	**24**	**25**	**27**	**28**	**29**
Range of years (EMFS)	1944-2013	1946-2010	1944-2013	1939-2014	1941-2014	1951-2014	1943-2014	1941-2014	1943-2014	1948-2011	1943-2014
Number of fires (EMFS)	67	34	51	555	650	84	232	521	449	3	414
Largest fire (EMFS)	409.3	106.4	228.3	1619.5	2556.7	675.2	4699.2	3251.5	2092.5	14.9	2607.7
EMFS 1.3 ratio (km2)	532.1	138.4	296.8	2105.3	3323.7	877.7	6109	4227	2720.3	19.4	3390
EMFS estimated (km2)	575.2	225.5	364.6	1678.5	2630.8	789.5	5567	3407.4	2194.8	170.1	2723.4
Iginition prob	2.52E-05	0.0002	6.7E-05	0.000277	0.000201	8.27E-05	0.000112	0.000277	0.000261	5.54E-06	0.000217
Escape prob	0.256098	0.067669	0.214286	0.355159	0.455172	0.384615	0.31	0.401674	0.319343	0.4	0.393258
Spread prob	0.232264	0.230822	0.23182	0.234525	0.235668	0.233753	0.229487	0.236881	0.236589	0.226192	0.23617
Method 4	**3**	**13**	**14**	**18**	**21**	**22**	**24**	**25**	**27**	**28**	**29**
Range of years (EMFS)	1944-2013	1946-2010	1944-2013	1939-2014	1941-2014	1951-2014	1943-2014	1941-2014	1943-2014	1948-2011	1943-2014
Number of fires (EMFS)	67	34	51	555	650	84	232	521	449	3	414
Largest fire (EMFS)	409.3	106.4	228.3	1619.5	2853.9	816.7	4699.2	3251.5	2092.5	14.9	2607.7
EMFS 1.3 ratio (km2)	532.1	138.4	296.8	2105.3	3710.1	1061.7	6109	4227	2720.3	19.4	3390
EMFS estimated (km2)	575.2	225.5	364.6	1678.2	2939.3	965.3	5561.1	3407	2194.5	170.1	2722.8
Iginition prob	2.52E-05	0.0002	6.7E-05	0.000277	0.000201	8.27E-05	0.000112	0.000277	0.000261	5.54E-06	0.000217
Escape prob	0.256098	0.067669	0.214286	0.355159	0.455172	0.384615	0.31	0.401674	0.319343	0.4	0.393258
Spread prob	0.232264	0.230822	0.23182	0.234547	0.235698	0.234113	0.229887	0.237006	0.236737	0.226192	0.236251

EMFS values are similar across methods 1, 3 and 4. Method 2 produces different results due to the inclusion of fires that cross the ecoregion boundary by less than 50%.

In the case of ecoregion 22, the point dataset did not contain the point for the largest polygon fire (*i.e.*, the point fell outside the ecoregion). This fire was more than 50% within the ecoregion, any of the polygon methods increase the largest fire size by including this fire, but the largest fire size varies depending on whether the clip method is used or the method that includes the full fire if >50% overlap. If Method 1 is to be used in future, a protocol could be developed to identify situations like this and add the missing point to the sample.

Conclusions

Method 3 or 4 produce the most accurate representation of the ecoregion's fire regime, and in most cases, produce very similar results. The choice will depend on whether fires with >50% of their area in the ecoregion should be counted with their full area or just their area that burned inside the ecoregion. In these examples, this only changes the EMFS in ecoregions 21 and 22. Since the results for methods 3 and 4 are similar to method 1, method 1 may be sufficient, especially in cases outside Alaska where the fire point and polygon data do not always share common IDs. This makes it difficult to remove duplicates when merging the datasets. If method 1 is used a protocol should be developed to manually identify any fire points that should be included in the sample (*i.e.,* large fires that have >50% of their area in the ecoregions but whose ignition points are outside the ecoregion).