Supplementary Information

1. Pre- and post-processing of training data and land cover classification results

Extensive training data from multiple sources is the foundation of our machine learning-based mapping algorithm. For this work, we leveraged existing high-quality data sources to compile our training data (see Methods). All such sources, however, include uncertainties and errors. To control for this, we used a machine-learning-based cross-validation procedure to identify training sites that provide only weak discrimination among classes of interest for each ecoregion, and then removed these sites from the training data set [1–3]. This pre-processing step removed less than 5% of the training sites in the full training set.

To create the final set of annual land cover maps, we post-processed classification results from random forest to reduce spurious land cover changes due to short-term climate variability or noise in the input data. To do this, we identified pixels exhibiting unlikely and/or repeated transitions between two classes (e.g., repeated changes between the Barren and Evergreen Forest, or frequent changes between Barren and Shrubland, and between Shrubland and Herbaceous classes). For pixels with more than six land cover changes of this nature within the 35-year study period, we reassigned the class label for the year before and after the transition to the mode of the land cover type across the time period. This conservative approach was affected less than 3% of pixels across the study area.

2. Reference point allocation and corrections for classification bias

Using our land cover and land cover change map results, we generated a stratification containing seven stable classes and six change classes (strata) to assess the accuracy of both stable land cover and land cover changes for the period 1986 to 2020. Each stratum was assigned a weight based on its area proportion in the initial map (i.e., in 1986), which informed our allocation of random samples for the reference dataset. The final set of reference samples was not allocated strictly proportional to area since the decision on total sample size, as well as the specific strata, reflects a balance among practicality, precision, and available human resources [4]. To eliminate issues arising from spatial correlation in reference data, we enforced a minimum 1 km distance between randomly selected reference samples. Each reference sample provides the land cover representative of a single Landsat pixel.

To determine the sample size (n) for our reference data set [5], we followed the methodology described and recommended by Olofsson et al. (2014) (Eq. 13) and :

$$n = \frac{(\Sigma\, W_i S_i)^2}{[S(O)] \;+\; (1/N)\Sigma W i S i^2} \approx \left(\frac{\Sigma W i S i}{S(O)}\right)$$

where $S(O)$ is the target standard error for the estimated overall accuracy that we aimed to achieve, W_i is the mapped proportion of class i, and S_i is the standard deviation of stratum i: $S_i = \sqrt{U_i(1 - U_i\,)}$ (where U_i is the user's accuracy for class i; see ref. (3), Eq 5.55). Given our large population size (N), the second term in the denominator is negligible. We specified a target standard error for overall accuracy of 0.01. We initially identified 2,265 reference points and removed 222 low-quality samples due to limited high-resolution imagery or ambiguous land cover, yielding a final set of 2,043 reference points.

We used the error matrix derived from our reference data to estimate the overall map and class-specific accuracies, area of changes, and associated uncertainties following the methods described in Olofsson et al.[3] and also detailed in Wang et al.[6] (Table S9-11). Area estimates were corrected using the reference samples and the error matrix to account for classification bias, and the final area proportions for each stratum were derived from the confusion matrix and the proportion of each stratum in the map. Uncertainty for each mapped area was determined using the standard error, providing a 95% confidence interval for the corrected area estimates.

Table S1: Stable land cover area between 1986 and 2020

Land Cover	**Area estimate (10^6 km^2)**	**Percentage of study domain**
Stable Land Cover		
Bare	0.32 ± 0.04	3.7%
DBF	0.84 ± 0.07	9.7%
ENF	2.84 ± 0.10	32.9%
Herbaceous	0.86 ± 0.07	10.0%
Shrubland	1.12 ± 0.10	13.0%
Water	1.23 ± 0.02	14.2%
Wetland	0.49 ± 0.06	5.6%

Table S2: Area disturbed by fire in each land cover and land cover change class between 1920 and 2020. Percentages show the percentage of total area in each class that was burned during each time period.

	1920 - 2020 Burned Area (km^2)	1920 - 2020 Burned Area Percentage	1985 - 2020 Burned Area (km^2)	1985 - 2020 Burned Area Percentage
Bare	3,383.1	1.21%	1,215.31	0.43%
DBF	78,717.3	10.46%	22,471.33	2.98%
ENF	440,676.9	15.65%	238,928.32	8.47%
Herbaceous	61,889.1	6.77%	31,116.59	3.40%
Shrubland	129,379.3	18.93%	77,171.57	11.28%
Water	48,459.6	3.95%	27,403.20	2.23%
Wetland	76,651.8	16.80%	43,495.33	9.54%
ENF Loss	327,268.7	67.98%	308,226.82	64.08%
DBF Gain	75,523.2	26.89%	38,160.07	13.58%
ENF Gain	84,355.8	28.11%	17,309.37	5.77%
DBF Loss	14,162.3	24.91%	10,678.29	18.77%
Shrubland Gain	35,960.1	23.18%	26,952.44	17.39%
Other Changes	41,238.4	17.57%	24,884.80	10.60%

Table S3: Matrix of stable and change classes. Colors indicate forest cover gain (green) versus forest cover loss (pink, tan) and shrubland gain (brown).

		To						
		Barren	**Forest DB**	**Forest EN**	**Herbaceous**	**Shrubland**	**Water**	**Wetland**
From	**Barren**	Stable	DB gain	EN gain	Other	Shrub gain	Other	Other
	Forest DB	DB loss	Stable	EN gain	DB loss	DB loss	DB loss	DB loss
	Forest EN	EN loss	DB gain	Stable	EN loss	EN loss	EN loss	EN loss
	Herbaceous	Other	DB gain	EN gain	Stable	Shrub gain	Other	Other
	Shrubland	Other	DB gain	EN gain	Other	Stable	Other	Other
	Water	Other	Other	Other	Other	Shrub gain	Stable	Other
	Wetland	Other	DB gain	EN gain	Other	Shrub gain	Other	Stable

Table S4: Matrix showing stable and changed land cover percentages before bias correction from 1986 to 2020 (Gray cells represent the stable classes)

		2020						
		Barren	Forest DB	Forest EN	Herbaceous	Shrub	Water	Wetland
1986	Barren	3.25	0.02	0.06	0.47	0.42	0.03	0.01
	Forest DB	0.02	8.75	0.51	0.35	0.18	0.01	0.10
	Forest EN	0.05	1.68	32.74	1.59	3.25	0.08	0.61
	Herbaceous	0.07	0.63	0.94	10.63	1.15	0.05	0.23
	Shrub	0.07	0.70	1.59	0.77	7.95	0.02	0.28
	Water	0.02	0.00	0.04	0.02	0.01	14.27	0.04
	Wetland	0.01	0.24	0.38	0.16	0.21	0.06	5.30

Table S5: Pixels disturbed by timber harvest in each land cover and land cover change class between 1986 and 2020. Note, timber harvest data only available for Canada.

	Harvest Area (km^2)	Area of harvest in the land cover class (%)
Bare	822.4	0.29%
DBF	40,721.9	5.41%
ENF	67,503.1	2.40%
Herbaceous	3,243.4	0.35%
Shrubland	908.5	0.13%
Water	322.4	0.03%
Wetland	2,063.6	0.45%
ENF Loss	56,676.9	11.77%
DBF Gain	48,584.2	17.30%
ENF Gain	4,741.2	1.58%
DBF Loss	14,638.4	25.75%
Shrubland Gain	517.0	0.33%
Other Changes	1,830.5	0.78%

Table S6: Area disturbed by fire (km^2), grouped according to age-cohort, in each land cover type. %'s show the percentage area for each cover time in each time cohort.

	Bare	**ENF**	**DBF**	**Herbaceous**	**Shrubland**	**Water**	**Wetland**
Pre-fire	2241.93	581955.92	37565.59	60002.17	106283.12	29332.48	67401.55
10-yr	3448.39	234706.59	29503.28	169472.08	329701.23	34812.68	90027.24
20-yr	2524.56	226136.72	36904.62	125276.91	283901.63	33194.63	81933.64
30-yr	1861.74	242391.81	56604.56	67017.25	198586.40	32337.42	75269.73
40-yr	1991.78	220035.83	58878.27	41754.42	113305.51	25782.91	55621.37
50-yr	1391.16	172323.43	63235.17	30224.29	56841.14	15572.13	33888.78
60-yr	1400.64	117182.66	56988.50	19295.44	32553.79	6795.13	19577.72
	Bare	**ENF**	**DBF**	**Herbaceous**	**Shrubland**	**Water**	**Wetland**
Pre-fire	0.25%	65.77%	4.25%	6.78%	12.01%	3.32%	7.62%
10-yr	0.32%	28.63%	4.67%	15.86%	35.94%	4.20%	10.37%
20-yr	0.28%	35.96%	8.40%	9.94%	29.46%	4.80%	11.17%
30-yr	0.38%	42.53%	11.38%	8.07%	21.90%	4.98%	10.75%
40-yr	0.37%	46.14%	16.93%	8.09%	15.22%	4.17%	9.07%
50-yr	0.55%	46.17%	22.45%	7.60%	12.83%	2.68%	7.71%
60-yr	0.76%	50.71%	21.95%	8.75%	9.20%	2.24%	6.38%

Table S7: Class definitions for the 1986 - 2020 land cover and land cover change map

Stable Land Cover Classes		
1	Bare/Sparsely vegetated	Lands with < 25% vegetation cover
2	Deciduous Broadleaf Forest (ENF)	Lands with > 25% tree cover, where tree species composition is > 75% deciduous broadleaf.
3	Evergreen Needleleaf Forest (DBF)	Lands with > 25% tree cover, where tree species composition is > 75% evergreen needleleaf
4	Mixed Forest (merged with DBF for accuracy assessment)	Lands with > 25% tree cover, where tree species composition of both evergreen and deciduous is < 75%
5	Herbaceous	Lands with unsaturated substrate, < 25% tree and < 25% shrub cover with > 25% herbaceous cover
6	Shrubland	Lands with unsaturated substrate, < 25% tree cover with > 25% shrubs (evergreen, deciduous)
7	Water	Areas with > 50% water cover
8	Wetland	Lands where substrate is saturated at least 10 months of most years and tree cover < 25%
9	Ice/Snow (exclude for accuracy assessment)	Lands > 50% persistent snow and ice cover
Land Cover Change Classes		
10	Evergreen Needleleaf Forest Loss	ENF to any non-forest class (bare/herbaceous/shrubland/water/wetland)
11	Deciduous Broadleaf Forest Gain	Any class, excluding water (ENF/herbaceous/shrubland/wetland) to DBF
12	Evergreen Needleleaf Forest Gain	Any class, excluding water (DBF/bare/herbaceous/shrubland/wetland) to ENF
13	Deciduous Broadleaf Forest Loss	DBF to bare/herbaceous/shrubland/water/wetland
14	Shrubland Gain	Conversion to shrubland from Barren/Herbaceous/water/Wetland
15	Other Changes	All other transitions not listed above

Table S8: Landsat-based spectral features used for CCDC and land cover mapping. Synthetic images are modeled from CCDC. SLP, INTP, COS, SIN, PHASE, AMPLITUDE and RMSE are computed from CCDC harmonic model fits at each pixel. TC refers to the 'tasseled cap' transformation of multispectral imagery; ρ refers to surface reflectance for Landsat bands.

Band or Index		**Description**
Green, Red, Blue, NIR, SWIR, SWIR2	SYNT	Synthetic images generated from CCDC model of each Landsat band
	SLP, INTP, COS, SIN	CCDC model intercept, slope, three sets of sine/cosine pairs, phase, and amplitude
	PHASE, AMPLITUDE	
	RMSE	The model root-mean-square error for each segment and input band
TC Wetness		TCW = 0.0315* ρ_blue + 0.2021*ρ_green + 0.3102*ρ_red + 0.1594*ρ_NIR + 0.6806* ρ_SWIR1 + 0.6109*ρ_SWIR2
TC Greenness		TCG = -0.1603* ρ_blue - 0.2819*ρ_green - 0.4934*ρ_red + 0.7940*ρ_NIR + 0.0002* ρ_SWIR1 + 0.1446*ρ_SWIR2
TC Brightness		TCB = 0.2043* ρ_blue + 0.4158*ρ_green + 0.5524*ρ_red + 0.5741*ρ_NIR + 0.3124* ρ_SWIR1 + 0.2303*ρ_SWIR2
World Settlement Footprint		Binary mask outlining the extent of human settlements circa 2015 at 10 m spatial resolution [7]
Worldpop Global Project Population		Estimated number of people residing in each grid cell circa 2010 at 100 m spatial resolution (www.worldpop.org)
TerraClimate		Monthly mean climate and climatic water balance for the period 1958 to 2020 at 4 km spatial resolution [8]
Global Surface Water		The frequency with which water was present, expressed as a percentage of time, from 1984 to 2015 at 30 m spatial resolution [9]
Topography		Slope, aspect, and elevation at 30 m spatial resolution. We used the Shuttle Radar Topography Mission (SRTM) wherever it was available and ALOS north of 60°N and south of 56°S where SRTM was not available [10,11]

Tables S9-11: Confusion matrix and accuracy assessment results comparing mapped classifications from 1986 and 2020 against reference data. The tables include (i) the confusion matrix with user/producer accuracies, (ii) a proportions table showing area estimates derived from reference data, and (iii) an uncertainty table reporting corresponding confidence intervals for the area estimates.

Sample Count

		Reference														
		Bare	DBF	ENF	Herb	Shrubland	Water	Wetland	ENF loss	DBF gain	ENF gain	DBF loss	Shrubland gain	Other	Total	User. Acc
Mapped	Bare	66	1	1	5	2	0	0	0	0	0	0	0	1	76	0.87
	DBF	0	138	17	0	5	0	1	0	3	0	0	0	0	164	0.84
	EF	2	18	538	3	26	1	6	10	1	1	0	0	0	606	0.89
	Herb	4	3	3	151	38	0	5	1	0	0	0	0	0	205	0.74
	Shrubland	2	2	18	10	169	2	5	0	0	1	0	0	0	209	0.81
	Water	1	0	2	0	0	279	1	0	0	0	0	0	0	283	0.99
	Wetland	1	2	6	3	14	1	72	0	0	0	0	0	0	99	0.73
	ENF loss	1	0	5	0	10	0	5	88	2	0	0	0	1	112	0.79
	DBF gain	0	13	5	1	0	0	1	1	32	2	1	0	0	56	0.57
	ENF gain	0	3	20	0	6	0	3	0	3	27	0	0	0	62	0.44
	DBF loss	0	4	0	5	1	0	3	0	0	0	31	0	1	45	0.69
	Shrubland gain	0	1	1	6	17	0	5	1	0	0	0	14	1	46	0.3
	Other	11	0	1	27	18	1	6	4	1	0	0	2	9	80	0.11
	Total	88	185	617	211	306	284	113	105	42	31	32	16	13	2043	
	Prod. Acc	0.75	0.75	0.87	0.72	0.55	0.98	0.64	0.84	0.76	0.87	0.97	0.88	0.69		0.79

Proportions																		
		Reference																
		Bare	DBF	ENF	Herb	Shrub	Water	Wetland	EN loss	DBF gain	ENF gain	DBF loss	Shrub gain	Other	Total	User. Acc	Mapped area (px)	Wi
Mapped	Bare	0.02811617	0.000426	0.000426	0.00213001	0.00085201	0	0	0	0	0	0	0	0.000426	0.0323762	0.87	3.11E+08	3.24%
	DBF	0	0.07331784	0.00903191	0	0.00265644	0	0.00053129	0	0.00159387	0	0	0	0	0.08713135	0.84	8.37E+08	8.71%
	ENF	0.00107571	0.00968136	0.289365	0.00161356	0.01398418	0.00053785	0.00322712	0.00537853	0.00053785	0.00053785	0	0	0	0.32593902	0.89	3.13E+09	32.59%
	Herb	0.00206529	0.00154897	0.00154897	0.0779647	0.01962026	0	0.00258161	0.00051632	0	0	0	0	0	0.10584612	0.74	1.02E+09	10.58%
	Shrub	0.00075707	0.00075707	0.00681363	0.00378535	0.06397244	0.00075707	0.00189268	0	0	0.00037854	0	0	0	0.07911384	0.81	7.60E+08	7.91%
	Water	0.00050221	0	0.00100442	0	0	0.14011592	0.00050221	0	0	0	0	0	0	0.14212475	0.99	1.36E+09	14.21%
	Wetland	0.00053331	0.00106663	0.00319988	0.00159994	0.00746638	0.00053331	0.03839851	0	0	0	0	0	0	0.05279796	0.73	5.07E+08	5.28%
	ENF loss	0.00049747	0	0.00248737	0	0.00497474	0	0.00248737	0.04377775	0.00099495	0	0	0	0.00049747	0.05571714	0.79	534929400	5.57%
	DBF gain	0	0.0075462	0.00290238	0.00058048	0	0	0.00058048	0.00058048	0.01857525	0.00116095	0.00058048	0	0	0.03250669	0.57	312090400	3.25%
	ENF gain	0	0.00168056	0.01120372	0	0.00336112	0	0.00168056	0	0.00168056	0.01512503	0	0	0	0.03473155	0.44	333450800	3.47%
	DBF loss	0	0.00058487	0	0.00073109	0.00014622	0	0.00043866	0	0	0	0.00453278	0	0.00014622	0.00657984	0.69	63171720	0.66%
	Shrub gain	0	0.00039032	0.00039032	0.00234193	0.00663546	0	0.0019516	0.00039032	0	0	0	0.00546449	0.00039032	0.01795476	0.3	172380200	1.80%
	Other	0.00373736	0	0.00033976	0.00917352	0.00611568	0.00033976	0.00203856	0.00135904	0.00033976	0	0	0.00067952	0.00305784	0.02718079	0.11	260957500	2.72%
	Total	0.0372846	0.09699981	0.32871336	0.09992058	0.12978492	0.14228391	0.05631065	0.05200244	0.02372224	0.01720237	0.00511325	0.00614401	0.00451786	1		9600805220	
	Prod. Acc	0.75	0.76	0.88	0.78	0.49	0.98	0.68	0.84	0.78	0.88	0.89	0.89	0.68		0.8		100.00%
	Area estimates (px)	357962136	931276322	3155912971	959318022	1246039726	1366040119	540627538	499265331	227752589	165156596	49091338.9	58987476.6	43375054.2				

Uncertainty														
		Reference												
		Bare	DBF	ENF	Herb	Shrub	Water	Wetland	ENF loss	DBF gain	ENF gain	DBF loss	Shrub gain	Other
Mapped	Bare	1.60E-06	1.81E-07	1.81E-07	8.59E-07	3.58E-07	0	0	0	0	0	0	0	1.81E-07
	DBF	0	6.21E-06	4.33E-06	0	1.38E-06	0	2.82E-07	0	8.36E-07	0	0	0	0
	ENF	5.78E-07	5.06E-06	1.75E-05	8.65E-07	7.21E-06	2.89E-07	1.72E-06	2.85E-06	2.89E-07	2.89E-07	0	0	0
	Herb	1.05E-06	7.92E-07	7.92E-07	1.07E-05	8.29E-06	0	1.31E-06	2.67E-07	0	0	0	0	0
	Shrub	2.85E-07	2.85E-07	2.37E-06	1.37E-06	4.66E-06	2.85E-07	7.03E-07	0	0	1.43E-07	0	0	0
	Water	2.52E-07	0	5.03E-07	0	0	9.98E-07	2.52E-07	0	0	0	0	0	0
	Wetland	2.84E-07	5.63E-07	1.62E-06	8.36E-07	3.45E-06	2.84E-07	5.64E-06	0	0	0	0	0	0
	ENF loss	2.47E-07	0	1.19E-06	0	2.27E-06	0	1.19E-06	4.71E-06	4.91E-07	0	0	0	2.47E-07
	DBF gain	0	3.42E-06	1.56E-06	3.37E-07	0	0	3.37E-07	3.37E-07	4.71E-06	6.62E-07	3.37E-07	0	0
	ENF gain	0	9.11E-07	4.32E-06	0	1.73E-06	0	9.11E-07	0	9.11E-07	4.86E-06	0	0	0
	DBF loss	0	7.97E-08	0	9.72E-08	2.14E-08	0	6.12E-08	0	0	0	2.11E-07	0	2.14E-08
	Shrub gain	0	1.52E-07	1.52E-07	8.13E-07	1.67E-06	0	6.94E-07	1.52E-07	0	0	0	1.52E-06	1.52E-07
	Other	1.11E-06	0	1.15E-07	2.09E-06	1.63E-06	1.15E-07	6.49E-07	4.44E-07	1.15E-07	0	0	2.28E-07	9.34E-07
	Standard errors	0.00232458	0.00420275	0.0058846	0.00423369	0.00571602	0.00140444	0.00370833	0.00295952	0.00271059	0.00244043	0.00074016	0.00132087	0.00123952
	Area std. Err. (px)	22317864.6	40349771.1	56496907.3	40646831.8	54878416.2	13483791.9	35602957	28413770	26023828.7	23430074.6	7106128.94	12681368.7	11900400
	95% CI	43743014.6	79085551.3	110733938	79667790.3	107561696	26428232.2	69781795.7	55690989.1	51006704.3	45922946.2	13928012.7	24855482.6	23324784

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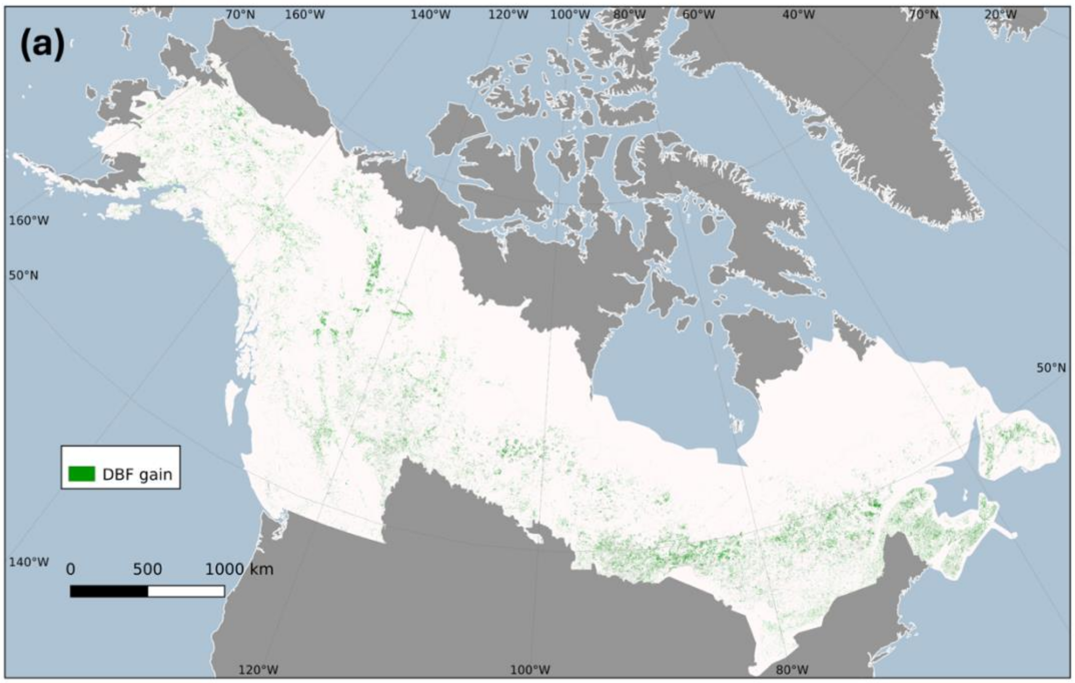
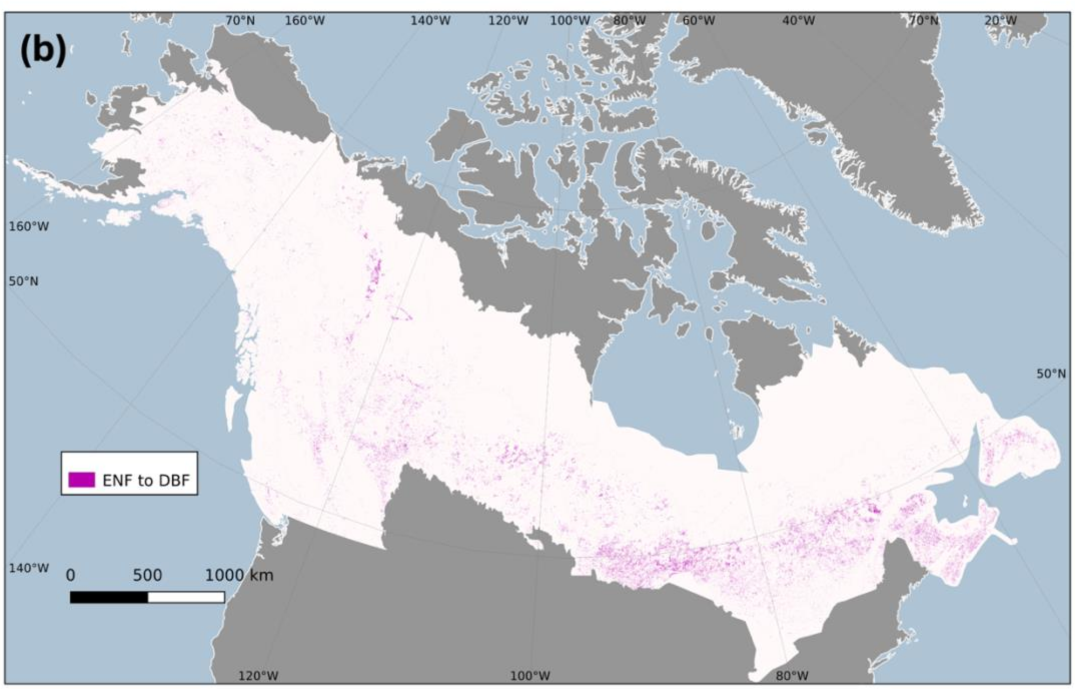
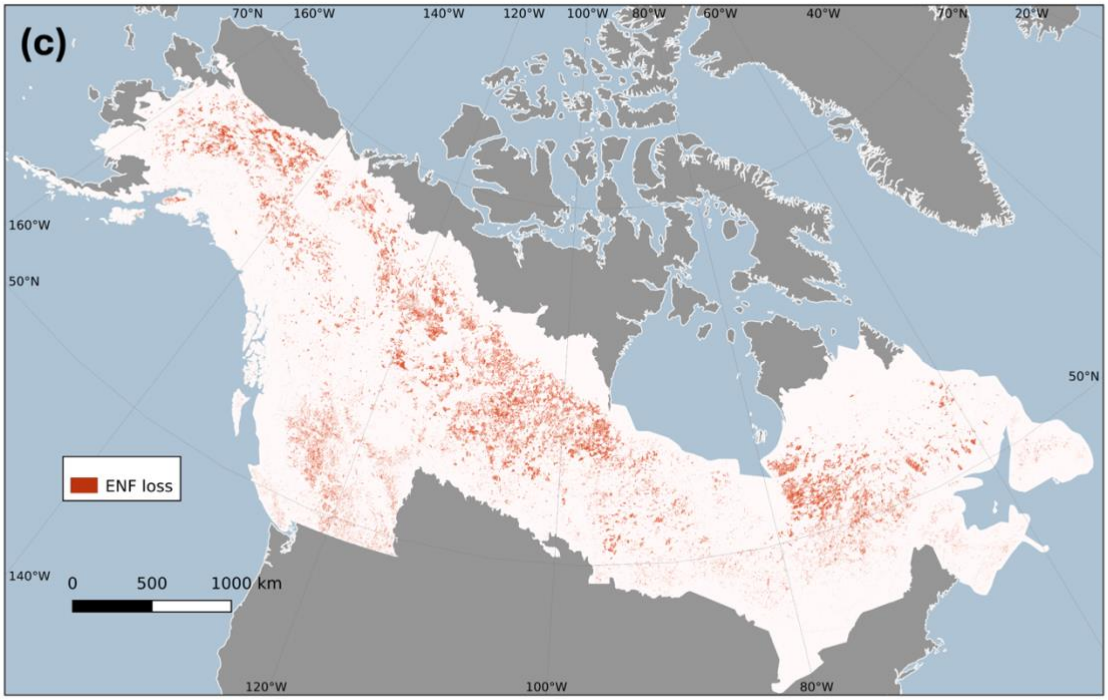
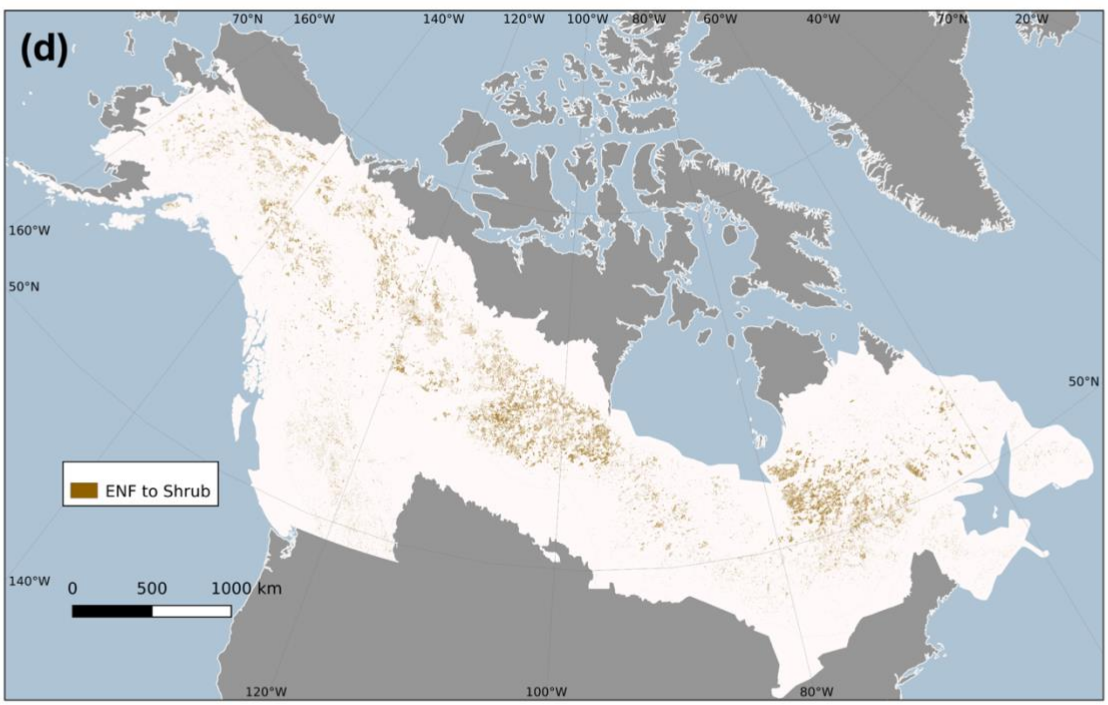
Figure S1: Maps showing evergreen needleleaf forest (ENF) and deciduous broadleaf forest (DBF) losses and gains between 1986-2020. 30 m pixels have been upscaled to 900 cells using the mode of the underlying land cover. (a) DBF gain from 1986-2020, (b) ENF to DBF, which is a subset of DBF gain (c) ENF loss, (d) ENF to Shrubland, which is a subset of ENF loss, (e) DBF loss, and (f) ENF gain.






(c)
ENF loss
0
500
1000 km
70°N
160°W
140°W
120°W
100°W
80°W
60°W
40°W
70°N
20°W
160°W
50°N
50°N
140°W
120°W
100°W
80°W


(d)
ENF to Shrub
0
500
1000 km
70°N
160°W
140°W
120°W
100°W
80°W
60°W
40°W
70°N
20°W
160°W
50°N
50°N
140°W
120°W
100°W
80°W


(e)
70°N
160°W
140°W
120°W
100°W
80°W
60°W
40°W
70°N
20°W
160°W
50°N
50°N
140°W
DBF loss
0
500
1000 km
120°W
100°W
80°W

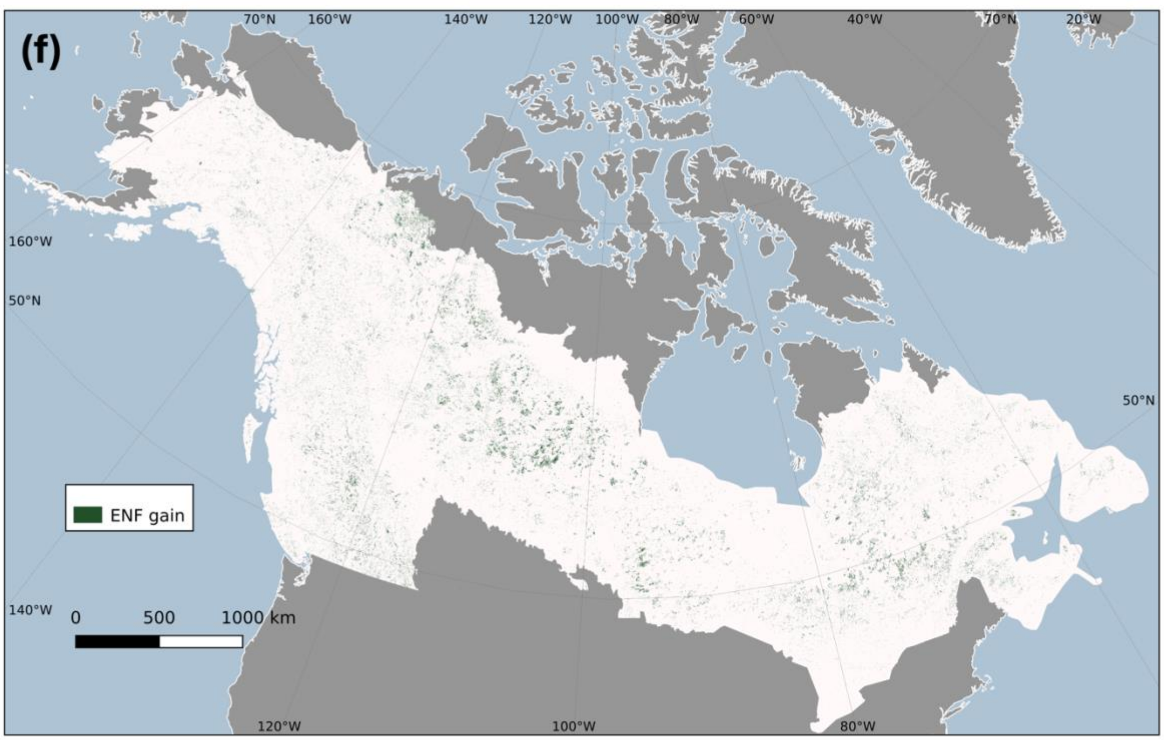

(f)
70°N
160°W
140°W
120°W
100°W
80°W
60°W
40°W
70°N
20°W
160°W
50°N
50°N
140°W
ENF gain
0
500
1000 km
120°W
100°W
80°W

Figure S2: Stratification used to analyze changes in land and forest cover in the main text.

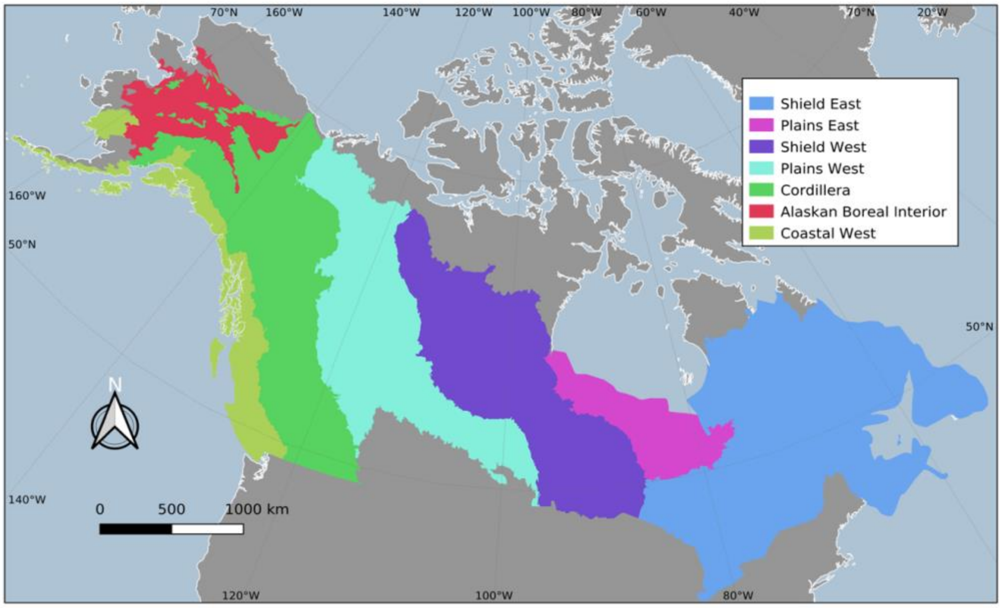
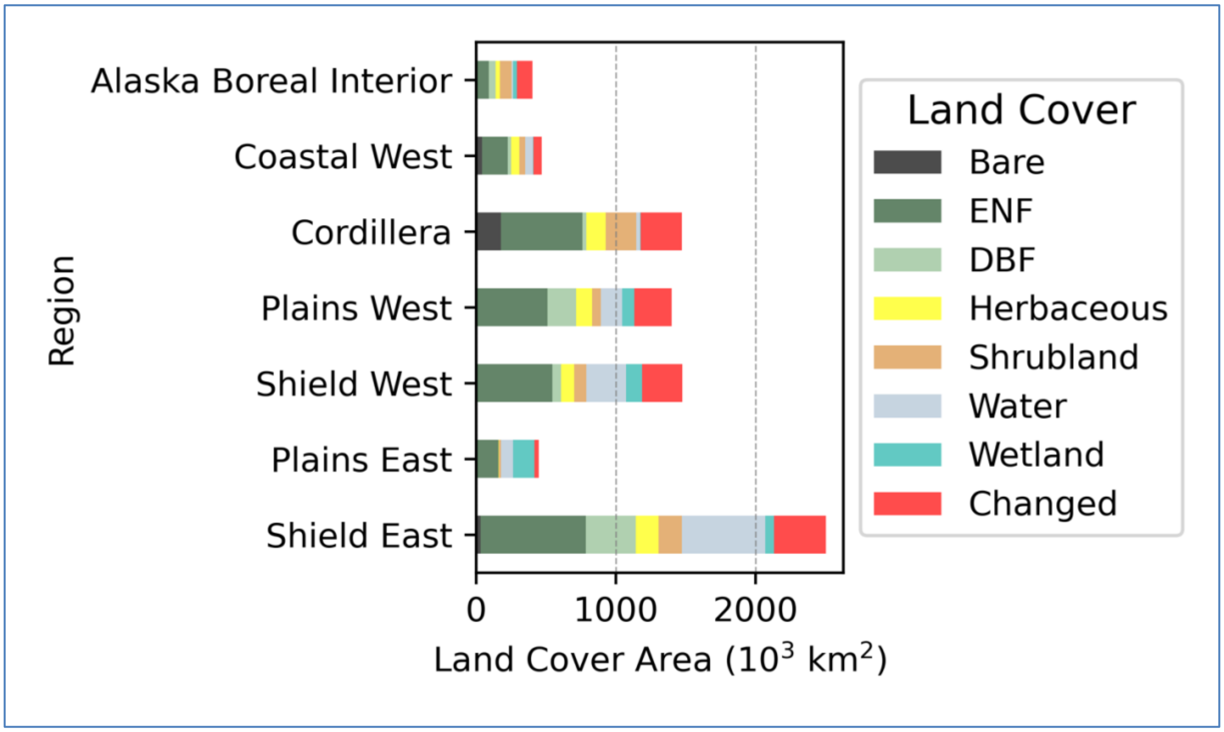


Figure S3: Stable (top) and changed (bottom) land cover areas for each ecoregion.



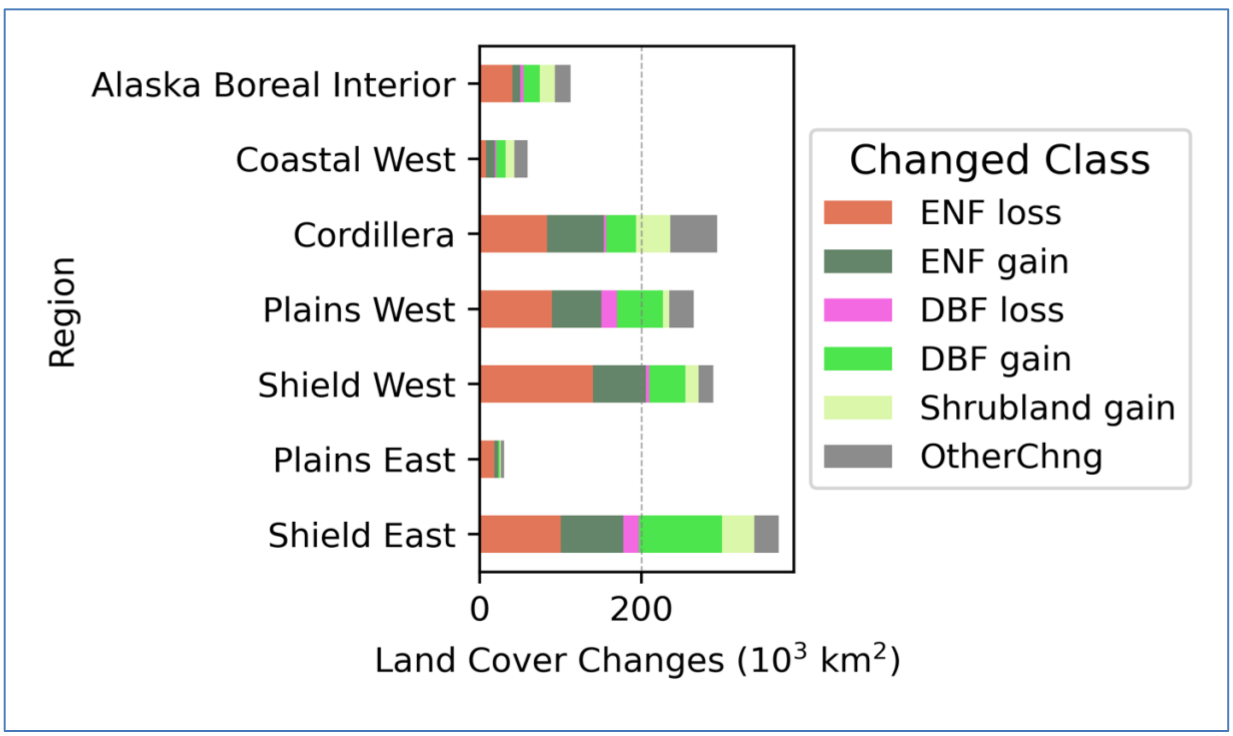


Figure S4: Example land cover results before and after fires in northwestern British Columbia. The upper left panel shows the extent and timing of fires from the Canadian National Fire Database.

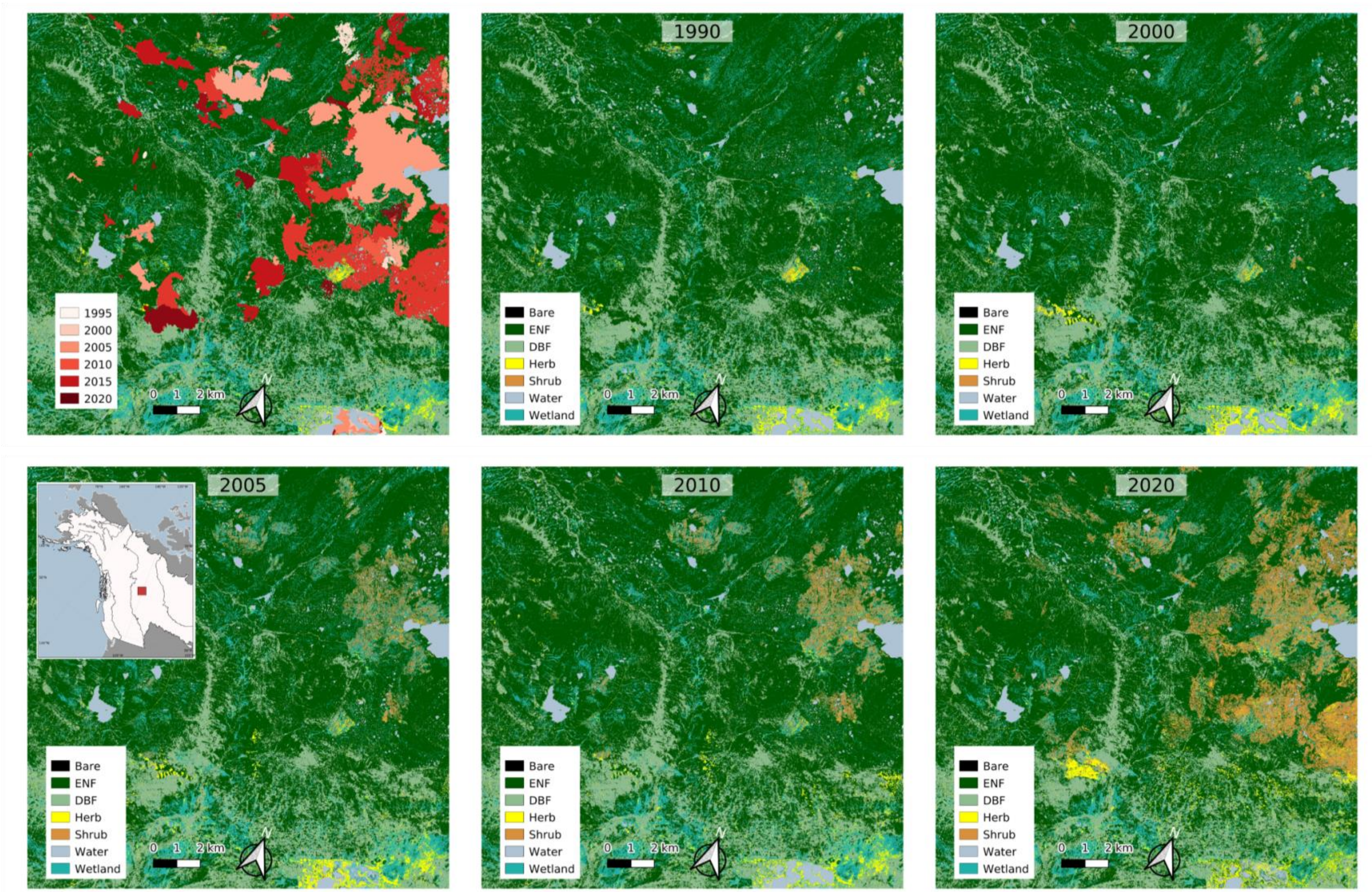


Figure S5: Changes in the proportional area of different land cover before and after timber harvest, based on timber harvest maps from the Canadian timber harvest disturbance map.

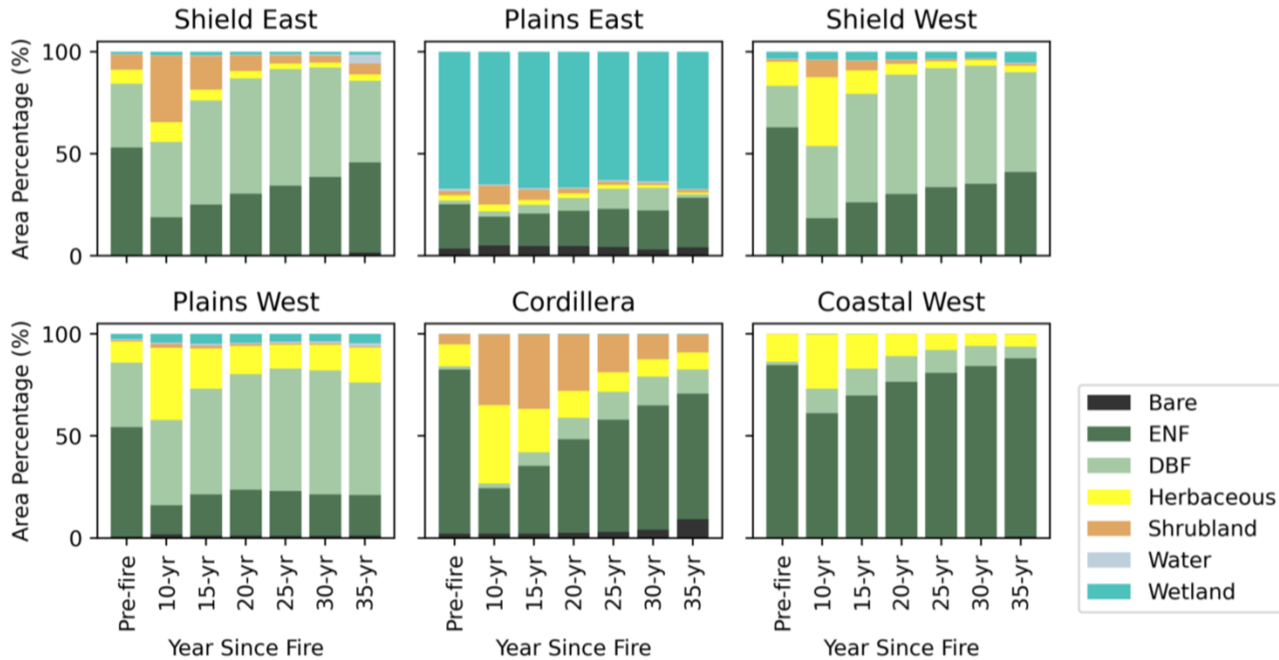


Figure S6: Changes in the proportional cover of different land cover types before and after fire, based on the fire disturbance map from Zhang et al.[12]. Relative to fire perimeters from Alaskan and Canadian databases, results showing post-fire land cover change in our results closely match those from Zhang et al.[12] and provide evidence that residual forest cover after fires shown in Figure 3 of the main text reflect errors in fire perimeters and islands of unburnt forest located within fire polygons.

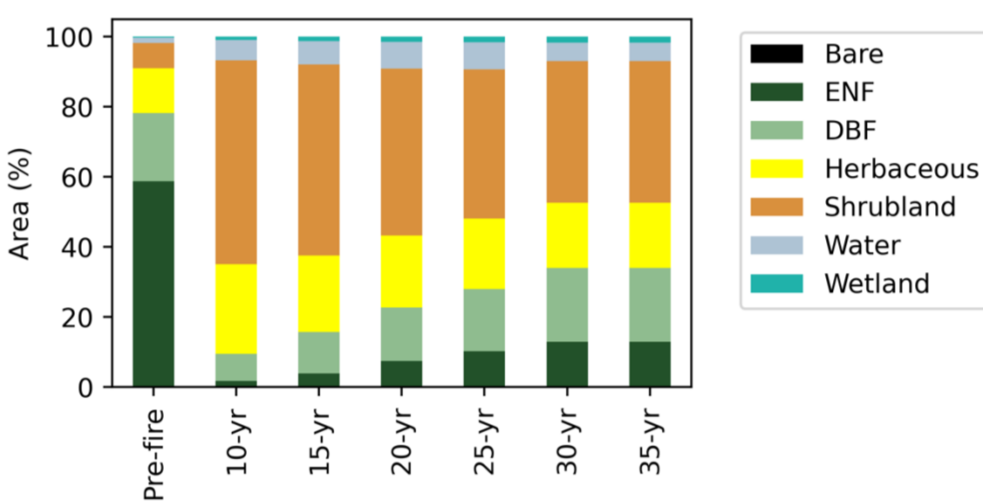


Figure S7: Distribution of the 67,340 training points, labeled by class, that were used to estimate random forest models used to perform the classification.

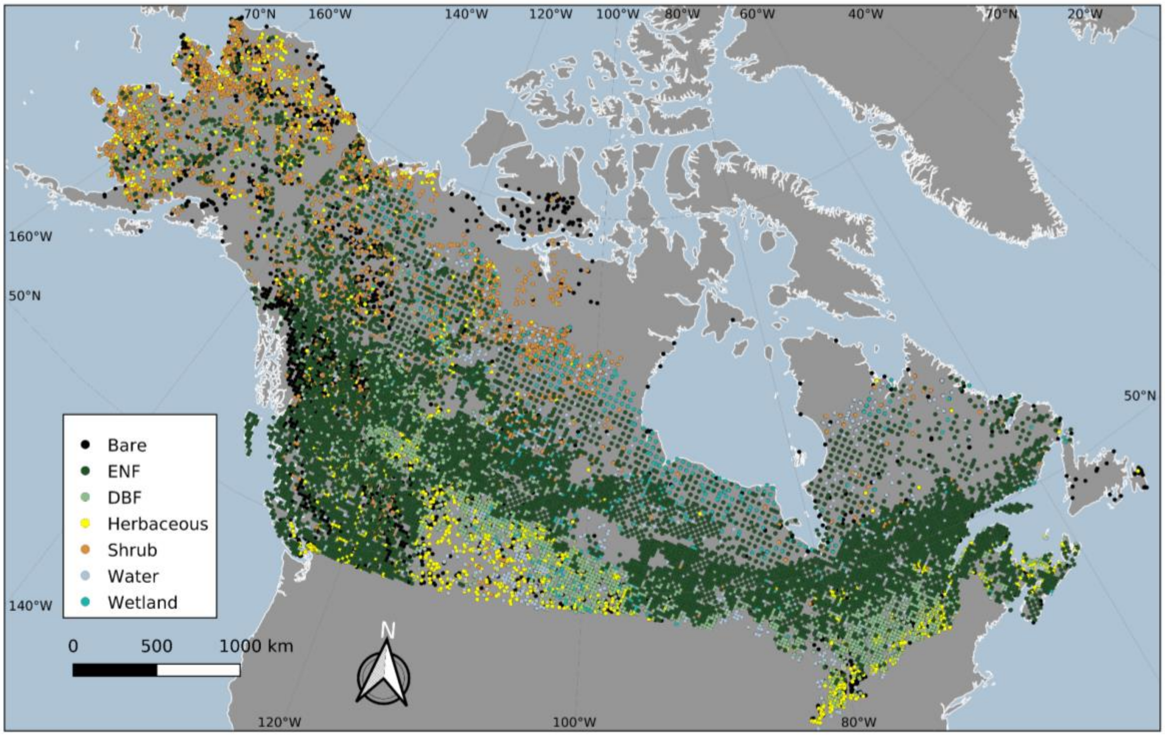
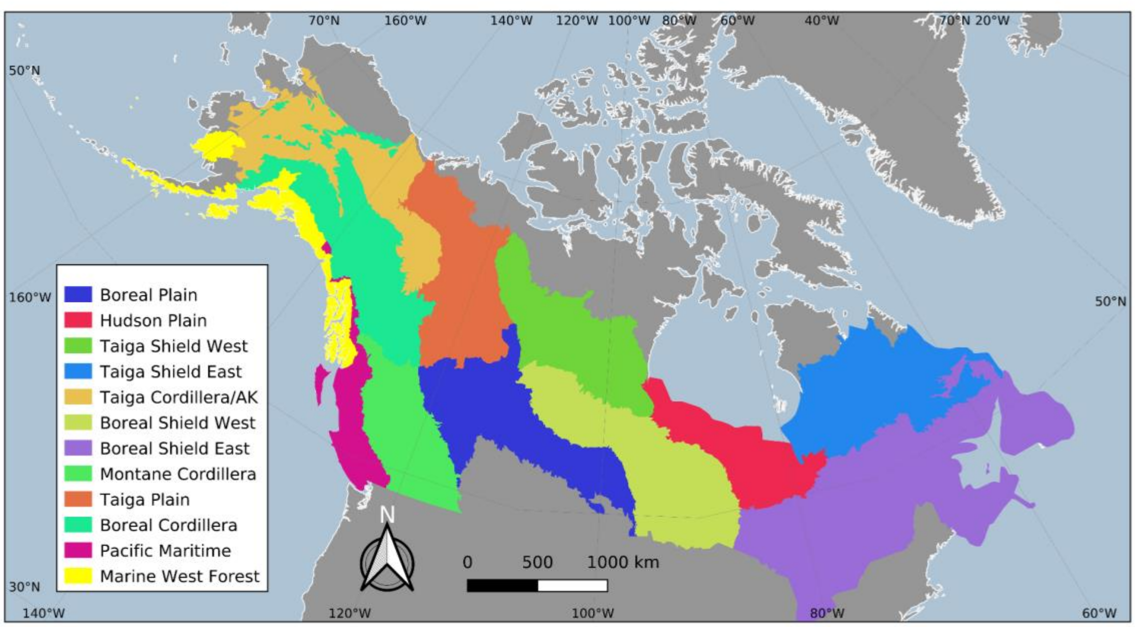


Figure S8: Ecoregions used for random forest mapping based on Level II USA EPA Ecoregions.



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