frontiers

Supplementary Material

1 Supplementary Text

1.1 Derivation of the portfolio hypothesis using the Leibniz product rule

The discretized version of the Leibniz product rule has been used and accepted across many disciplines. Note that $\Delta(c_i \cdot p_i)$ is simply the difference in $c_i \cdot p_i$ before (with subscript b) and after (with subscript a) a shift. i.e.,

$$\begin{aligned}\Delta(c_i \cdot p_i) &= c_{i,a} \cdot p_{i,a} - c_{i,b} \cdot p_{i,b} = c_{i,a} \cdot p_{i,a} - c_{i,b} \cdot p_{i,a} + c_{i,b} \cdot p_{i,a} - c_{i,b} \cdot p_{i,b} \\ &= \Delta c_i \cdot p_{i,a} + c_{i,b} \cdot \Delta p_i\end{aligned}$$

That is,

$$\Delta(c_i \cdot p_i) = \Delta c_i \cdot p_{i,a} + c_{i,b} \cdot \Delta p_i$$

Similarly,

$$\begin{aligned}\Delta(c_i \cdot p_i) &= c_{i,a} \cdot p_{i,a} - c_{i,b} \cdot p_{i,b} = c_{i,a} \cdot p_{i,a} - c_{i,a} \cdot p_{i,b} + c_{i,a} \cdot p_{i,b} - c_{i,b} \cdot p_{i,b} \\ &= \Delta c_i \cdot p_{i,b} + c_{i,a} \cdot \Delta p_i\end{aligned}$$

That is,

$$\Delta(c_i \cdot p_i) = \Delta c_i \cdot p_{i,b} + c_{i,a} \cdot \Delta p_i$$

Consequently, we have

$$\Delta(c_i \cdot p_i) = \Delta c_i \cdot p_i + c_i \cdot \Delta p_i$$

where p_i and c_i as specified in the main text "the mean values of past and present periods."

1.2 Description of *in situ* forest-tree data

Forest Inventory and Analysis (FIA) is a nationwide survey of the extent and status of forests (Burrill et al., 2021). The plots are permanent sample plots from which data are collected annually on a portion of plots to achieve complete surveys recurring every 5-7 years. The FIA plots are approximately 0.1 ha in size and are placed on a hexagonal grid so that there is one plot for every 2,428 ha (6,000 acres) of forested land. In order to maintain the privacy of landowners, all plot coordinates are spatially perturbed as required by the Food Security Act of 1985. However, true coordinates are within 0.80 to 1.61 km of the fuzzed coordinates, so the impact is negligible (Burrill et al., 2021). The Cooperative Alaska Forest Inventory (CAFI) provides a collection of permanent sample plots in southeast Alaska, and the plot size is 0.04 ha in a square shape (Malone et al., 2009). The data from permanent sample plot networks of Canada is distributed across eight provinces – British Columbia, Alberta, Saskatchewan, Manitoba, Ontario, Quebec, Nova Scotia, and Newfoundland and Labrador. These plots are 0.04 ha in size, and their distributions over forested

areas and re-measurement frequency vary slightly among provinces (Chen et al., 2016). The data from Canada's National Forest Inventory ground plot network is distributed across the forested areas in Canada, and their plot size differs (125–500 m^2) (National Forest Inventory, 2011; Zhang et al., 2017).

1.3 Plot-to-grid aggregation

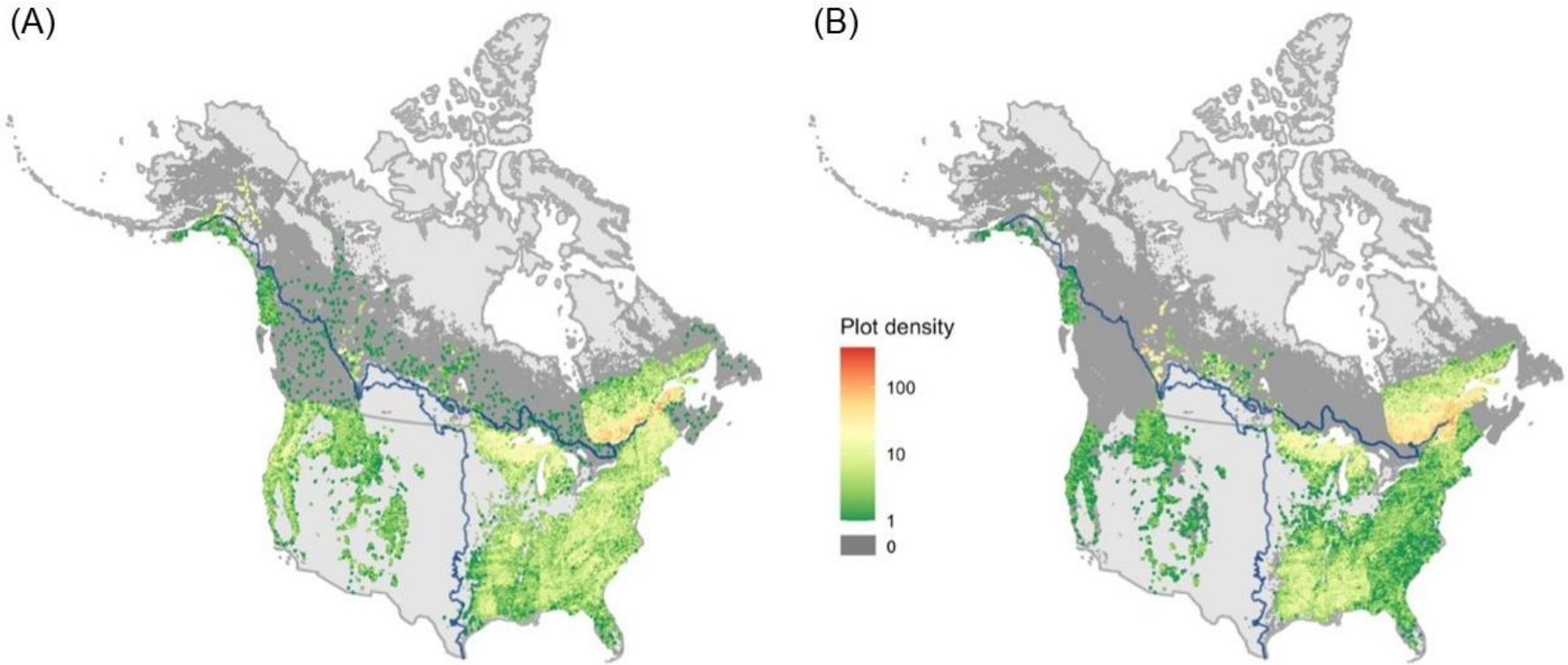
Assume that a species has *n* individuals in a grid cell and *y* individuals in a plot, with the plot size divided by grid cell size being *a*. According to previous research (Green and Plotkin, 2007), assuming either a Poisson or a negative-binomial distribution, the expectation $E(y)$ for both distribution is $a \cdot n$. Even without assuming a specific distribution, the number *y* will follow a hyper-geometric distribution (Hui et al., 2011) and the expectation of the hyper-geometric distribution $E(y)$ is again $a \cdot n$. Therefore, it is reasonable to aggregate plot-level species importance value index (IVI) into the grid level using the mean function.

1.4 Description and architecture of autoencoder neural networks

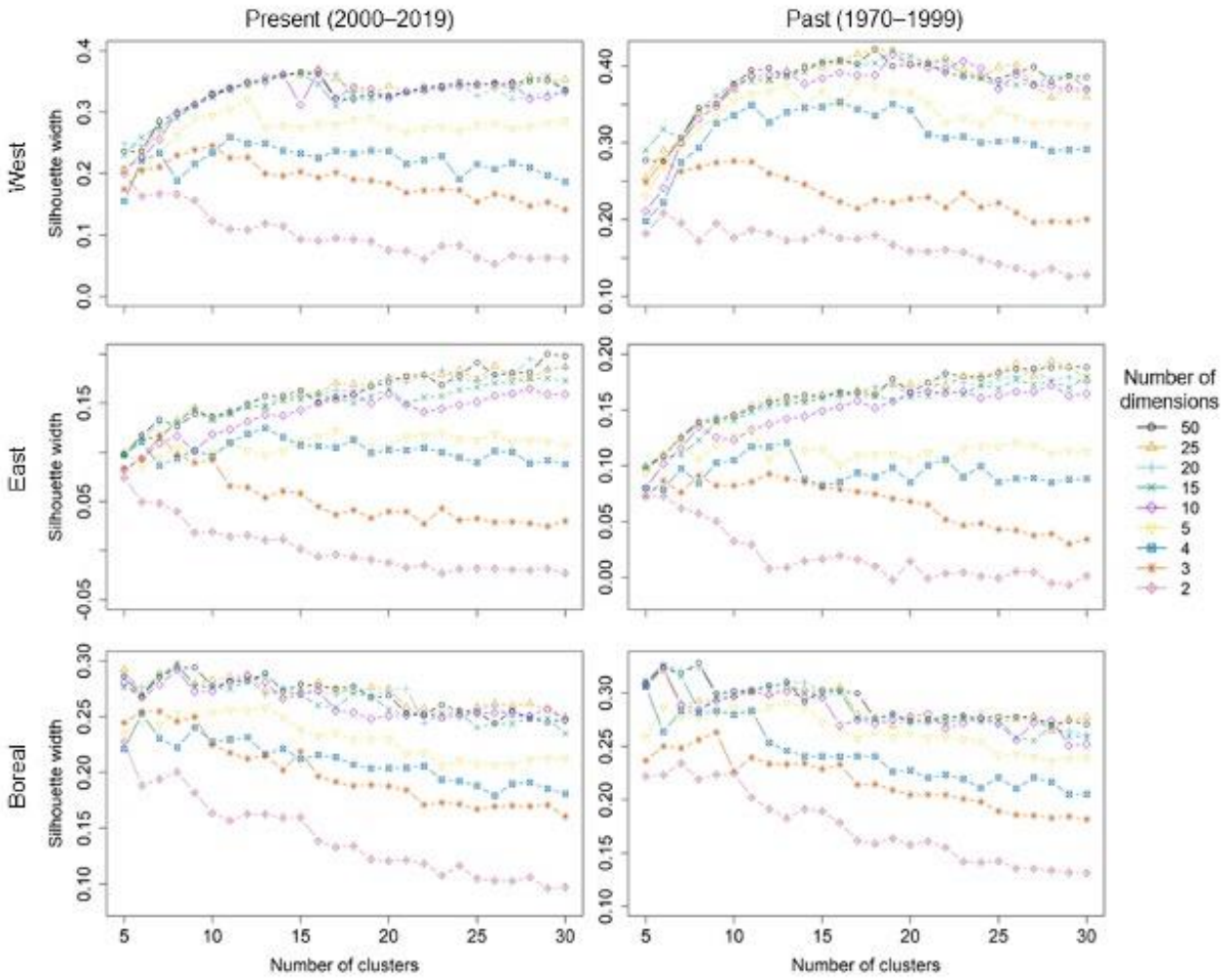
Autoencoder neural networks are unsupervised deep learning models, which use the nonlinear generalization of principal component analysis used to reduce dimensions in data (Goodfellow et al., 2016; Hinton and Salakhutdinov, 2006). Autoencoders learn to decompose input data into alternate representations using an encoding function, $e: R^n \rightarrow R^k$, and then reconstruct an approximation of the input using a decoding function, $d: R^k \rightarrow R^n$, where the parameters of function e and d are simultaneously optimized (Goodfellow et al., 2016). Both the encoding and decoding functions are comprised of one or more layers to perform z operations between the input and model parameters, where z is the number of units in each layer. The result of all z operations in each layer can then be transformed using a non-linear activation function, $\sigma(\cdot)$, to reveal characteristics of the data distribution in an alternate dimensional space (Song et al., 2014). This approach provides a more informative data distribution along with the data's reduced dimensionality for efficient data transformations. In this work, we used the autoencoders' encoding function, $e: R^n \rightarrow R^k$, where $k < n$, to transform the input data into a reduced dimensional representation to conduct K-means cluster analysis. The reduced dimensional representation of the input information improves robust clustering results and mitigates the computational complexity of the K-means algorithm ($O(n^2)$). We began by constructing a fully connected autoencoder comprised of an input layer (with n units) followed by three fully-connected layers (consisting of 150, $0.75 * n$, and 150 units, respectively) and the n-dimensional output layer. The output of each fully-connected layer was given by $\sigma(x \cdot w + b)$, where $x, w \in R^p$ and $b \in R$ denote the layer's input, the number of units in each layer, and the threshold bias value, respectively. Note that p represents an arbitrary dimensionality of any given layer. The three hidden layers used a linear activation function, and the output layer utilized a sigmoid activation function, which is given by $\sigma(\frac{1}{1+\exp(x \cdot w+b)})$ that provides values between 0 and 1. This sigmoid activation function in the output layer made the overall network non-linear while all the three hidden layers utilized a linear activation function. The encoder, e, and the decoder, d, were simultaneously optimized according to $\min_{e,d} \left|\left|\frac{1}{n}\sum_{i=1}^{n}(x_i - d(e(x_i))\right|\right|^2$ using the Adam optimizer (Hinton and Salakhutdinov, 2006). After training the autoencoder, the output of the second hidden layer was used to encode the input into its reduced dimensional representation, which was then inputted into the K-means clustering algorithm.

2 Supplementary Figures and Tables

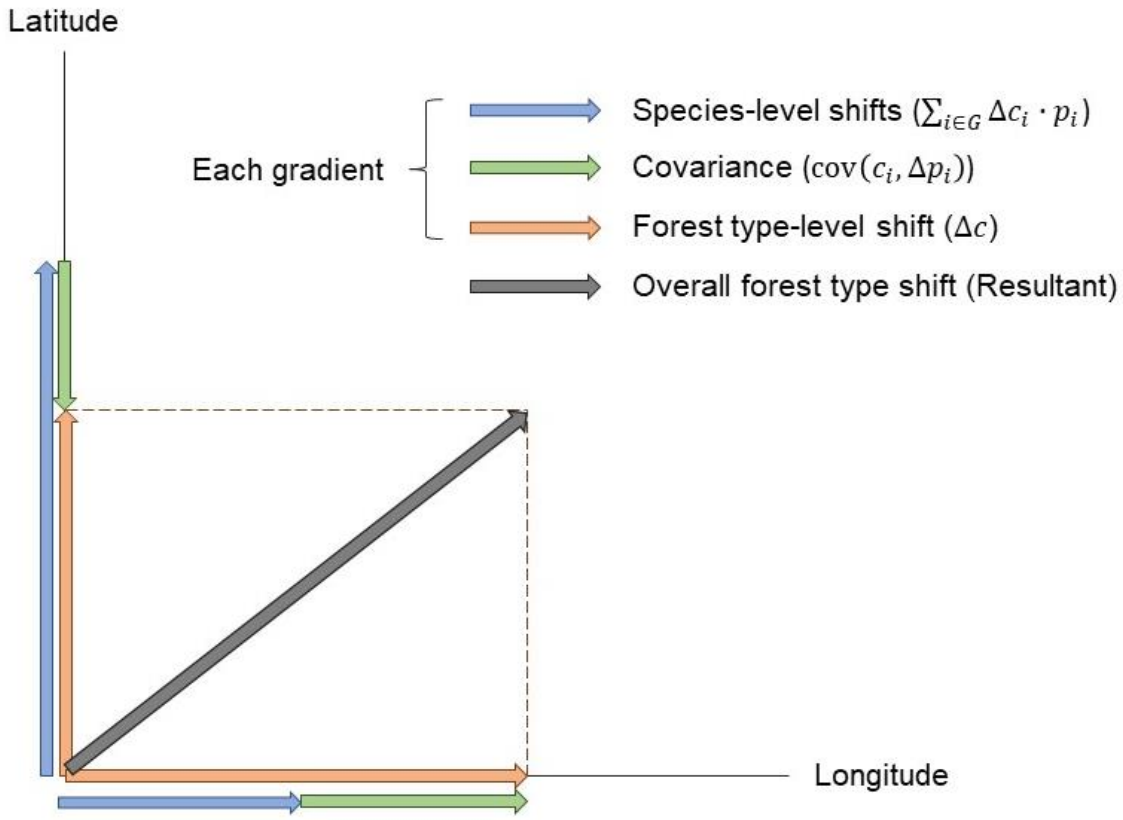
2.1 Supplementary Figures



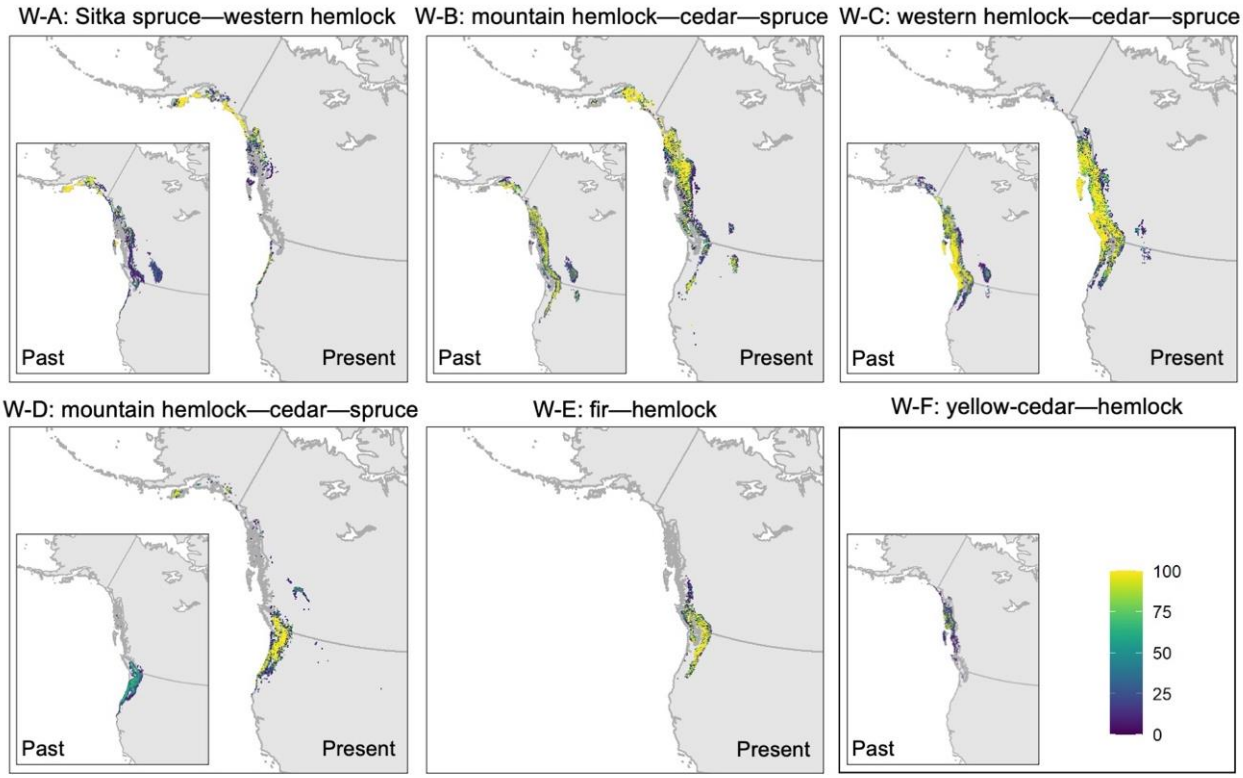
Supplementary Figure 1. Forest inventory plot density for the (A) present (2000–2019) and (B) past (1970–1999) dataset within the forested areas with a minimum 10% canopy cover 2000 (Hansen et al., 2013) in accordance with FAO's definition of 'forest' (FAO, 2020). Plot density represents the number of sample plots per 0.1×0.1° grid (~100 km2). Thick line indicates the border between three arch-biomes: West, East, and Boreal.



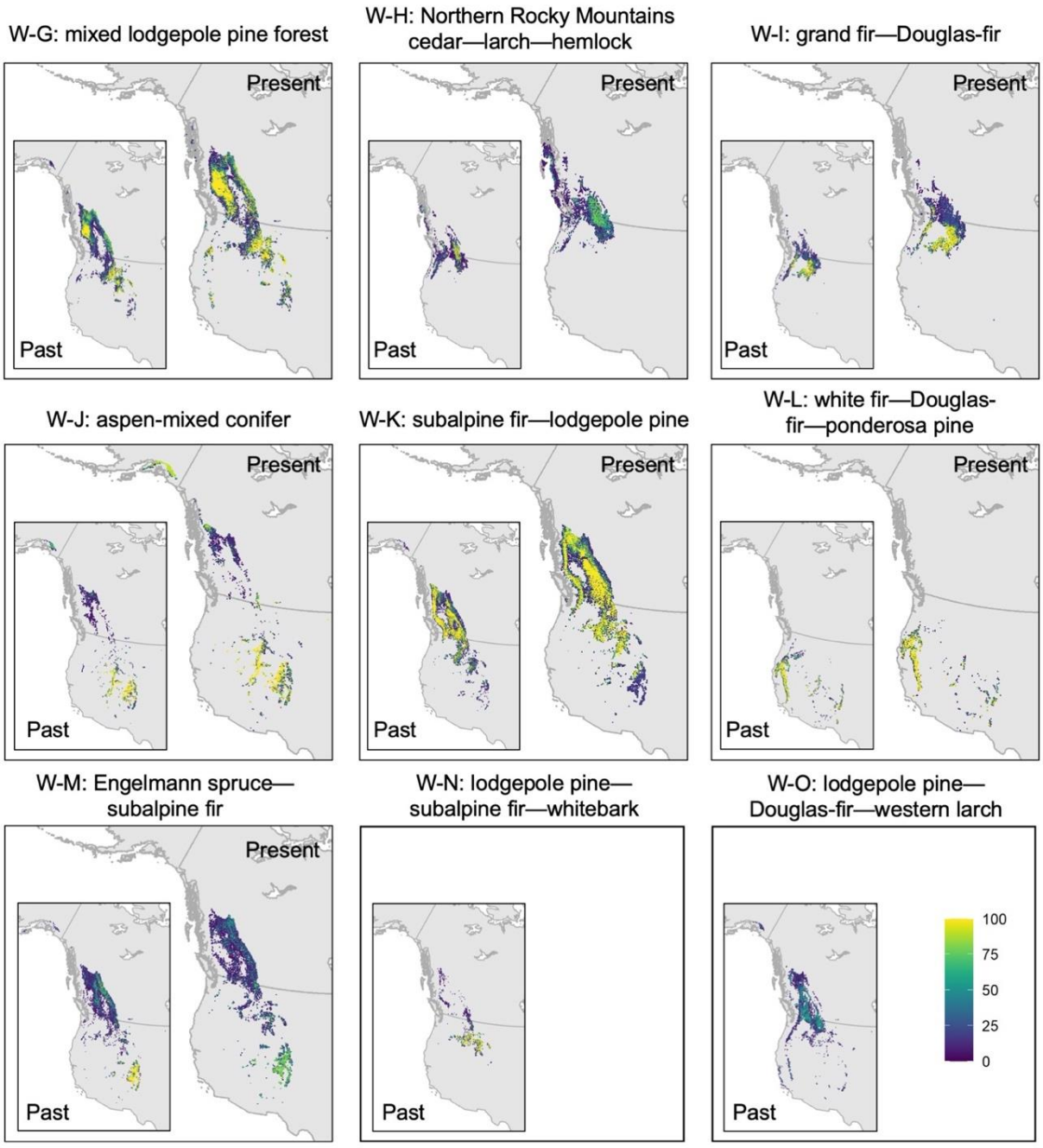
Supplementary Figure 2. Average silhouette width with a different number of clusters and a number of dimensions obtained from autoencoder neural network. Since silhouette width does not improve above number of dimensions = 15, we chose 15 as the number of dimensions for all models. Due to the data size, we used 90% of the present East dataset to conduct K-means cluster analysis and calculate silhouette width.



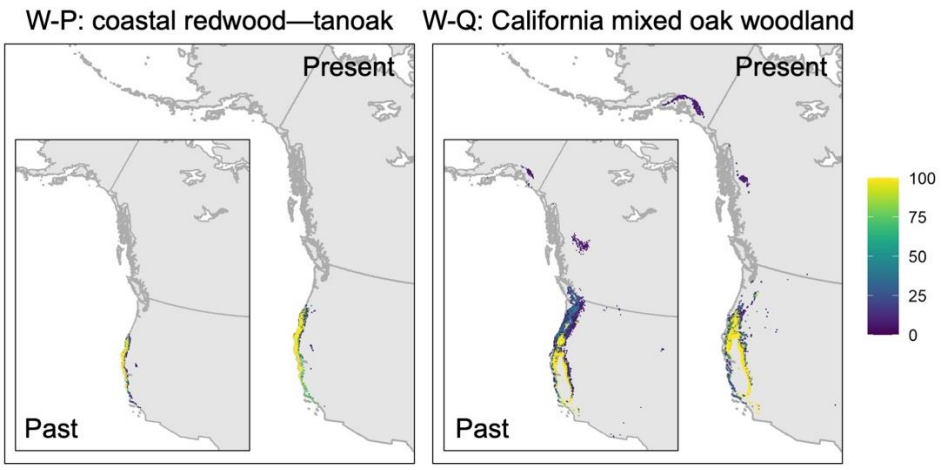
Supplementary Figure 3. We quantified the weighted sum of species-level shifts ($\sum_{i\in G} \Delta c_i \cdot p_i$), the covariance (the portfolio effect, $\mathrm{cov}(c_i, \Delta p_i)$), and the sum of the two (i.e., forest type-level shift (Δc)) for each forest type along each latitudinal and longitudinal gradient. The resultant of the two forest type-level shifts (black arrow) represents the overall forest type shift in a two-dimensional space.



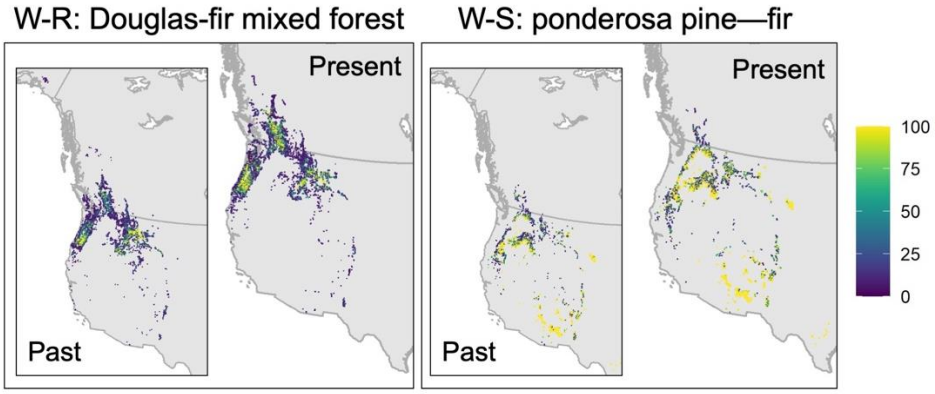
Supplementary Figure 4. Geographic distribution of predicted percent forest type of the present (2000–2019) and past (1970–1999) in the Pacific Coastal Forest biome. Percent forest type was calculated based on how many repetitions, out of 20, returned the given forest type in each grid cell (see 2.5. Forest type mapping).



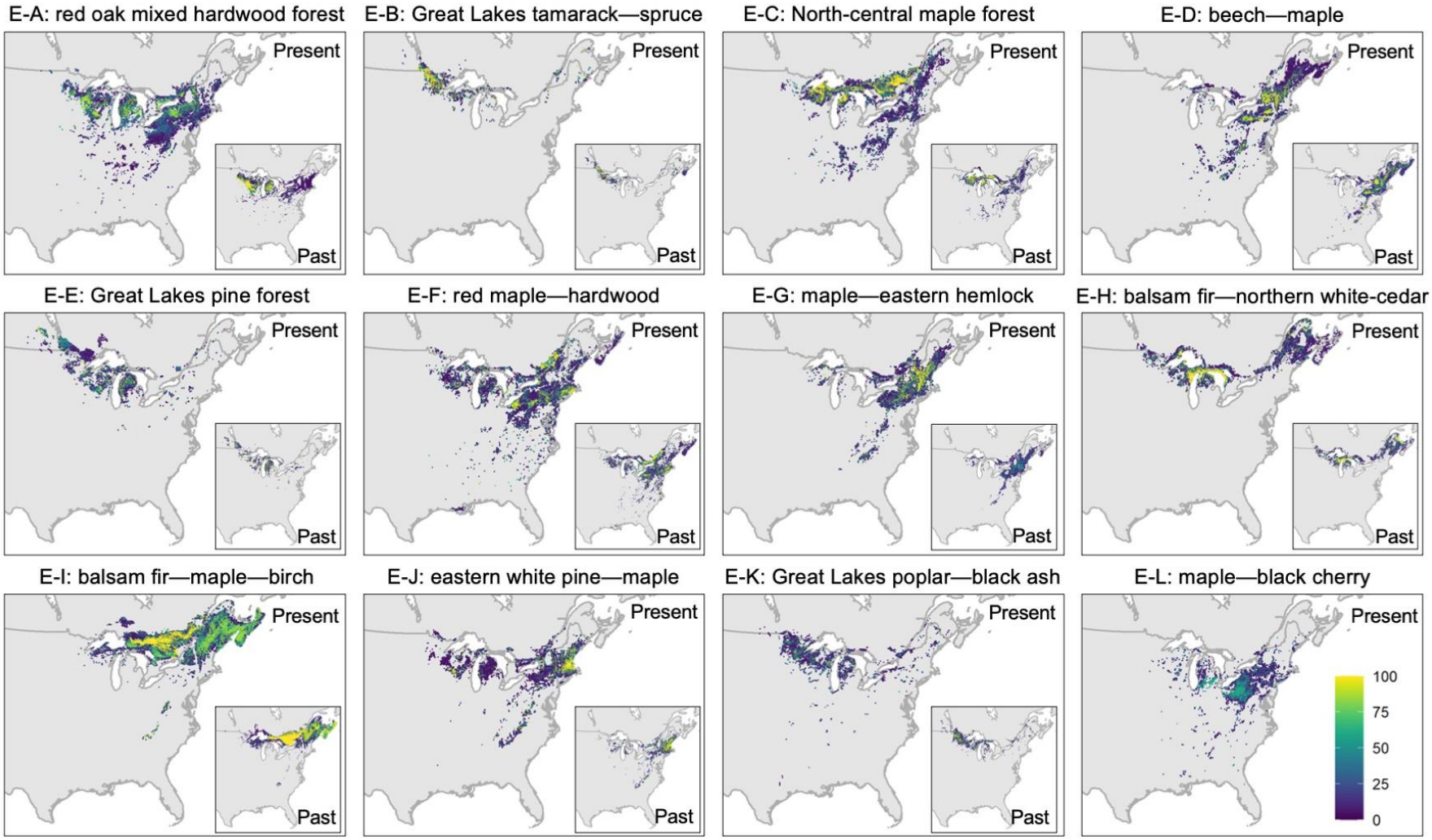
Supplementary Figure 5. Geographic distribution of predicted percent forest type of the present (2000–2019) and past (1970–1999) in the Western Cordillera biome. Percent forest type was calculated based on how many repetitions, out of 20, returned the given forest type in each grid cell (see 2.5. Forest type mapping).



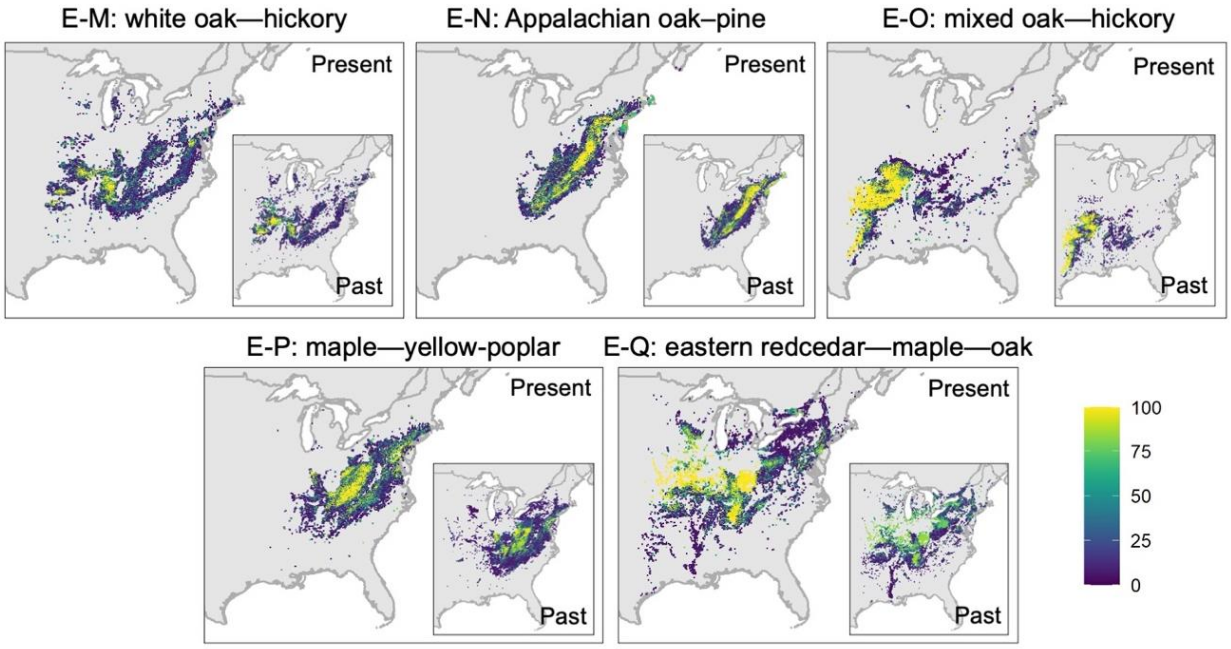
Supplementary Figure 6. Geographic distribution of predicted percent forest type of the present (2000–2019) and past (1970–1999) in the Mediterranean California biome. Percent forest type was calculated based on how many repetitions, out of 20, returned the given forest type in each grid cell (see 2.5. Forest type mapping).



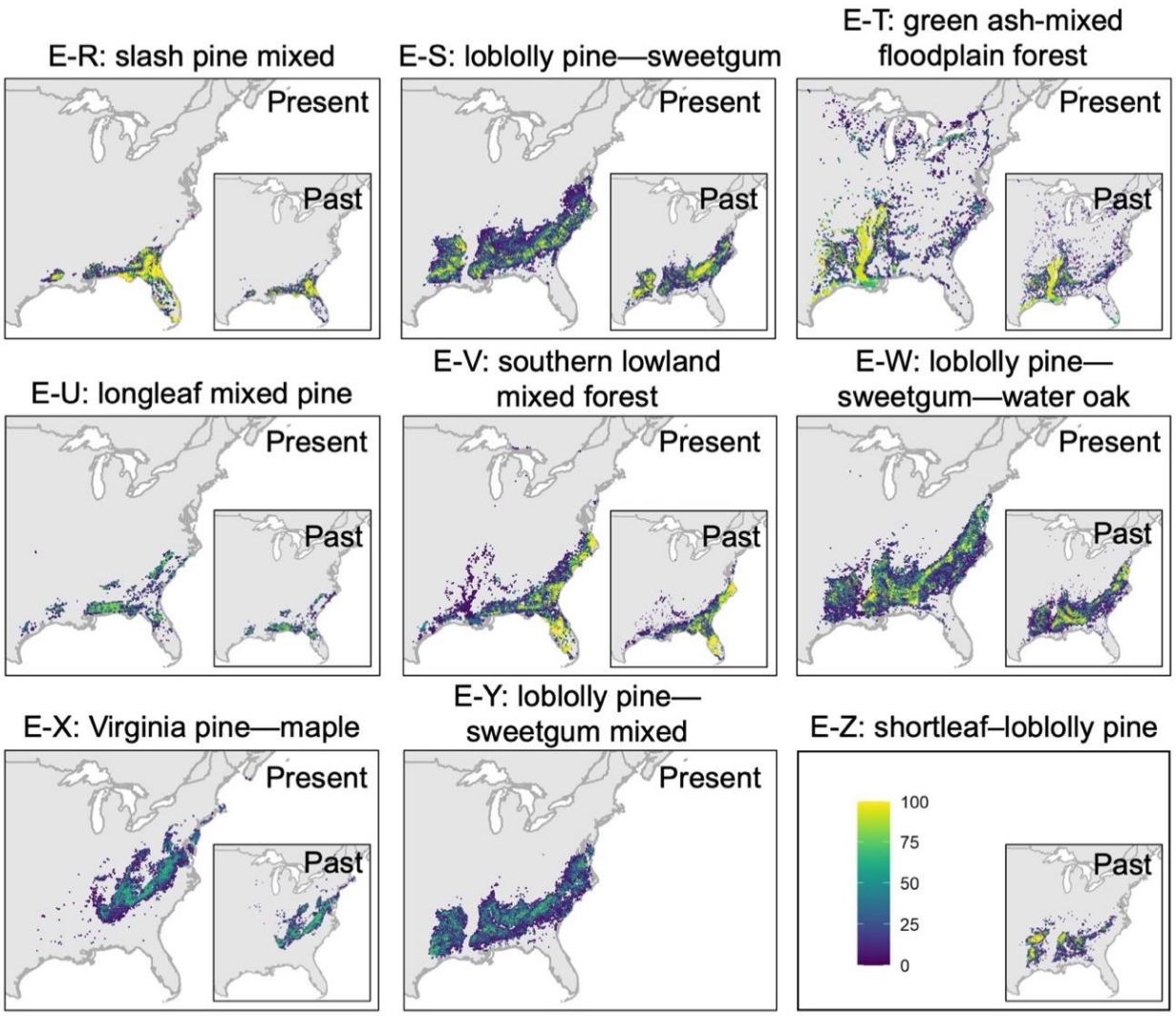
Supplementary Figure 7. Geographic distribution of predicted percent forest type of the present (2000–2019) and past (1970–1999) in the Coastal-Interior Range biome. Percent forest type was calculated based on how many repetitions, out of 20, returned the given forest type in each grid cell (see 2.5. Forest type mapping).



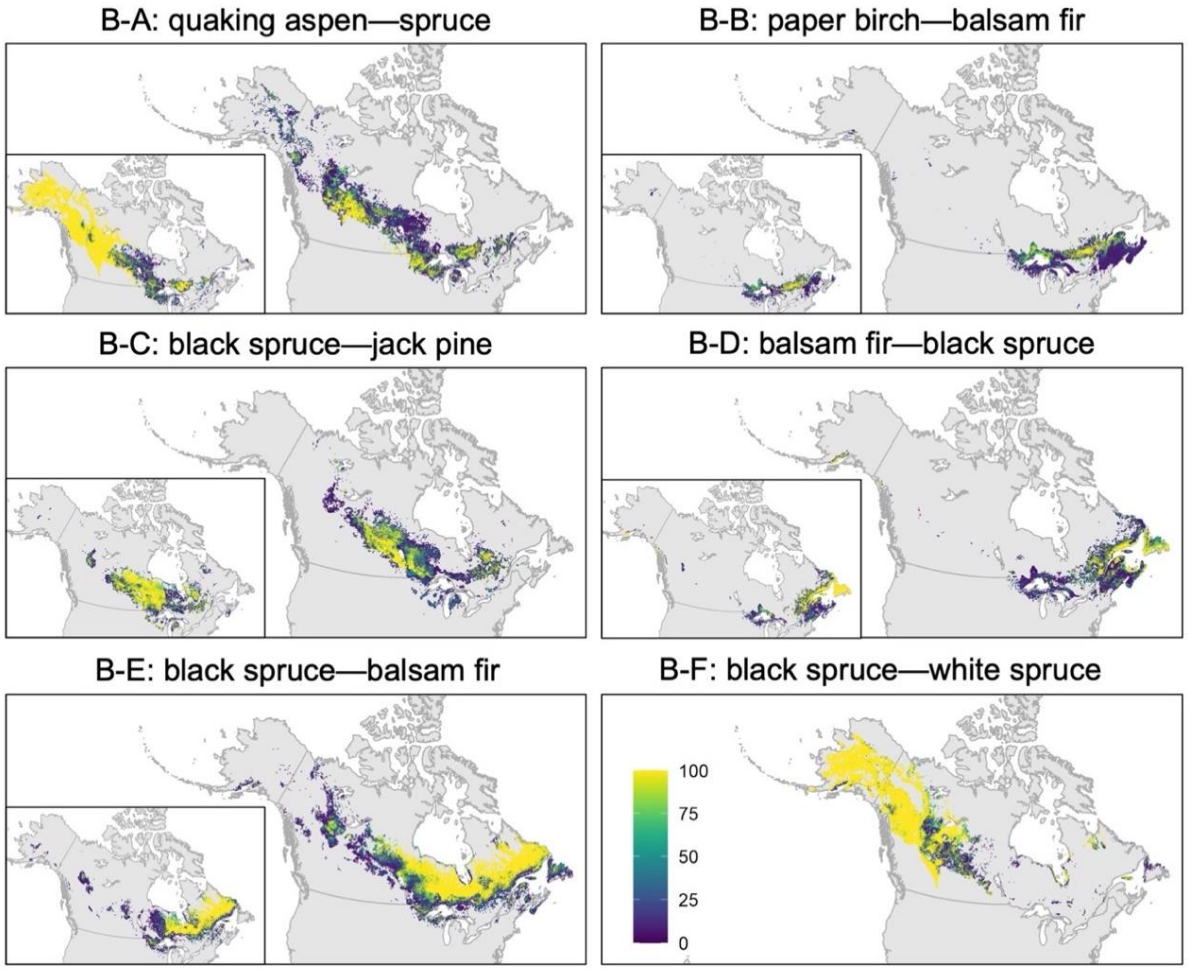
Supplementary Figure 8. Geographic distribution of predicted percent forest type of the present (2000–2019) and past (1970–1999) in the Eastern Mixed Forest biome. Percent forest type was calculated based on how many repetitions, out of 20, returned the given forest type in each grid cell (see 2.5. Forest type mapping).



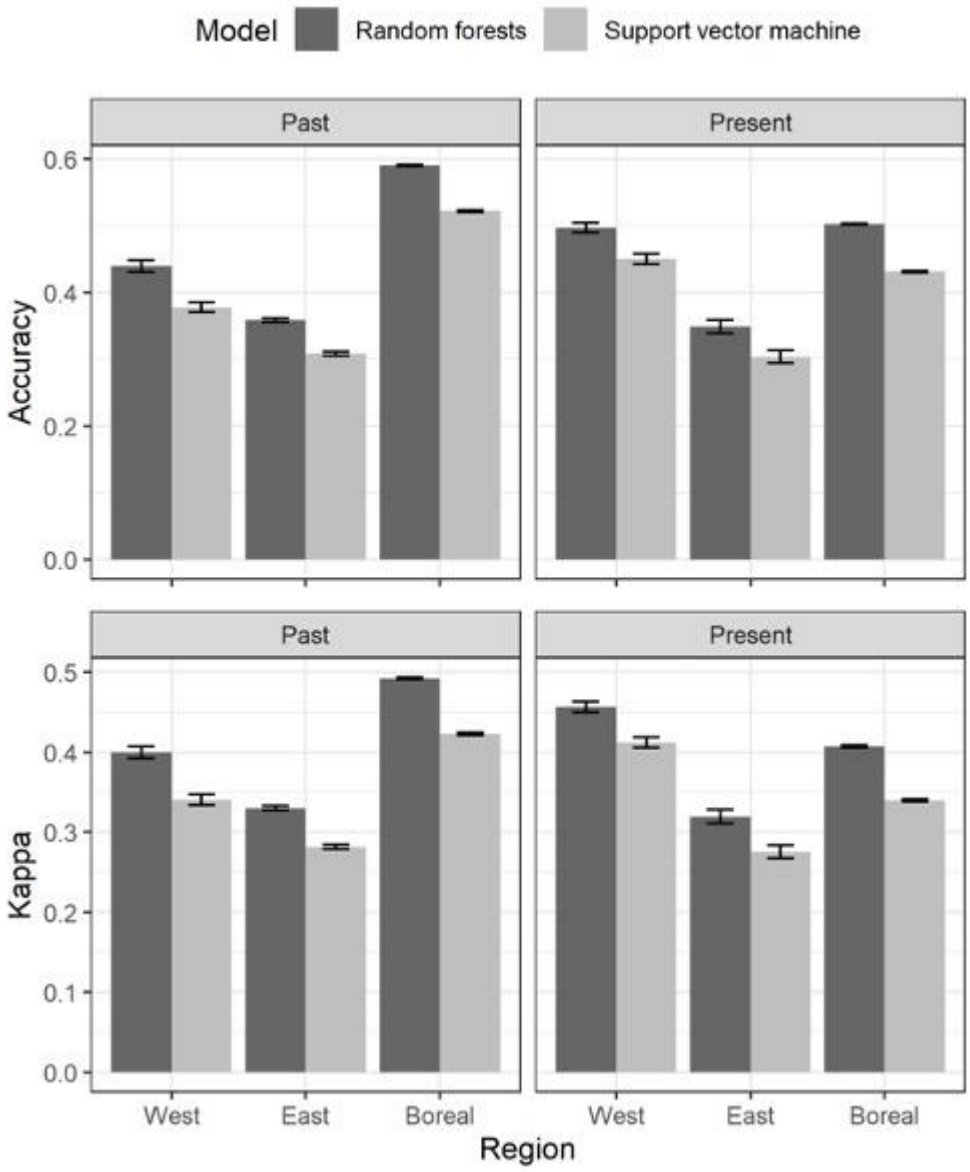
Supplementary Figure 9. Geographic distribution of predicted percent forest type of the present (2000–2019) and past (1970–1999) in the Central Forest biome. Percent forest type was calculated based on how many repetitions, out of 20, returned the given forest type in each grid cell (see 2.5. Forest type mapping).



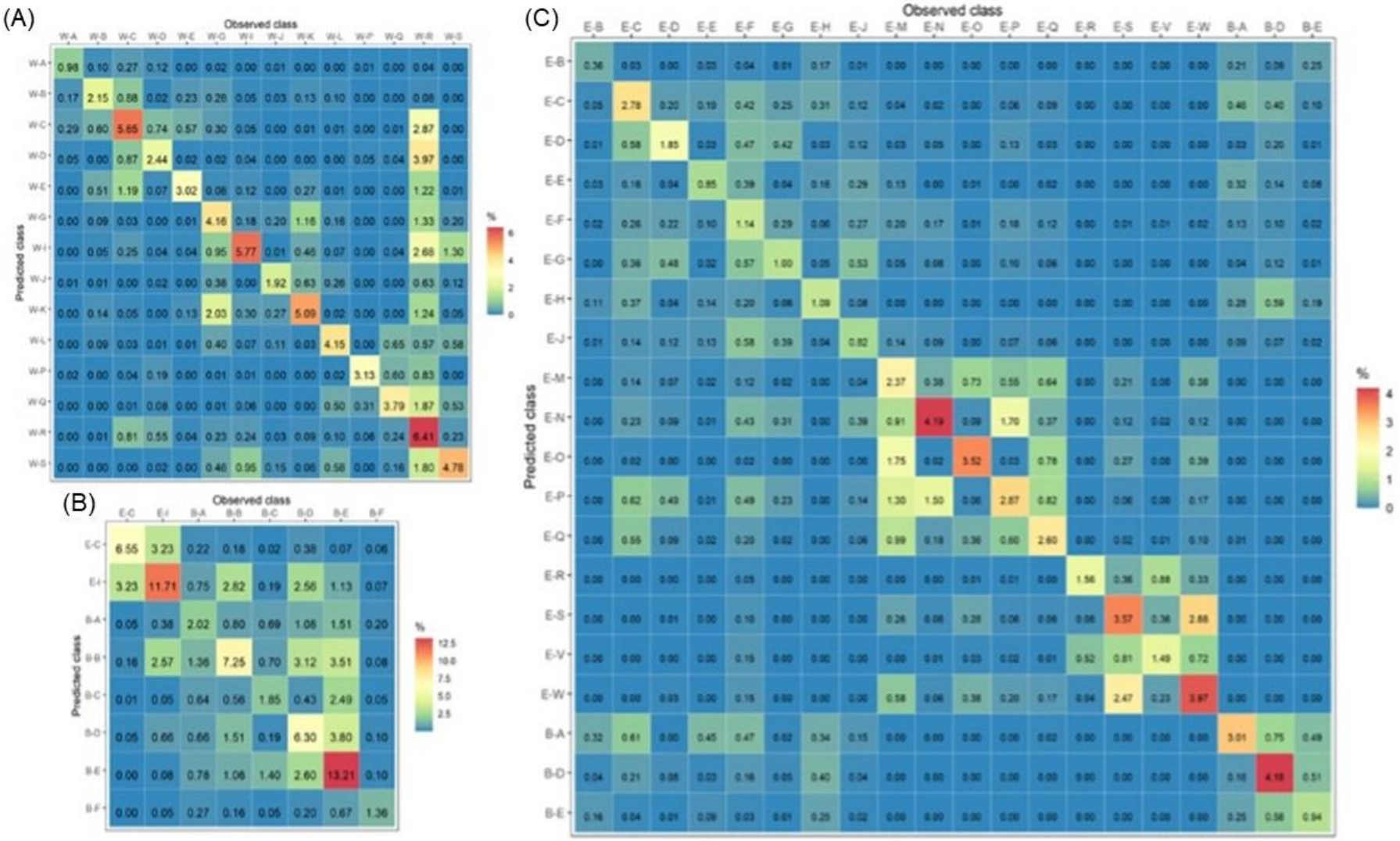
Supplementary Figure 10. Geographic distribution of predicted percent forest type of the present (2000–2019) and past (1970–1999) in the Southeastern Plains biome. Percent forest type was calculated based on how many repetitions, out of 20, returned the given forest type in each grid cell (see 2.5. Forest type mapping).



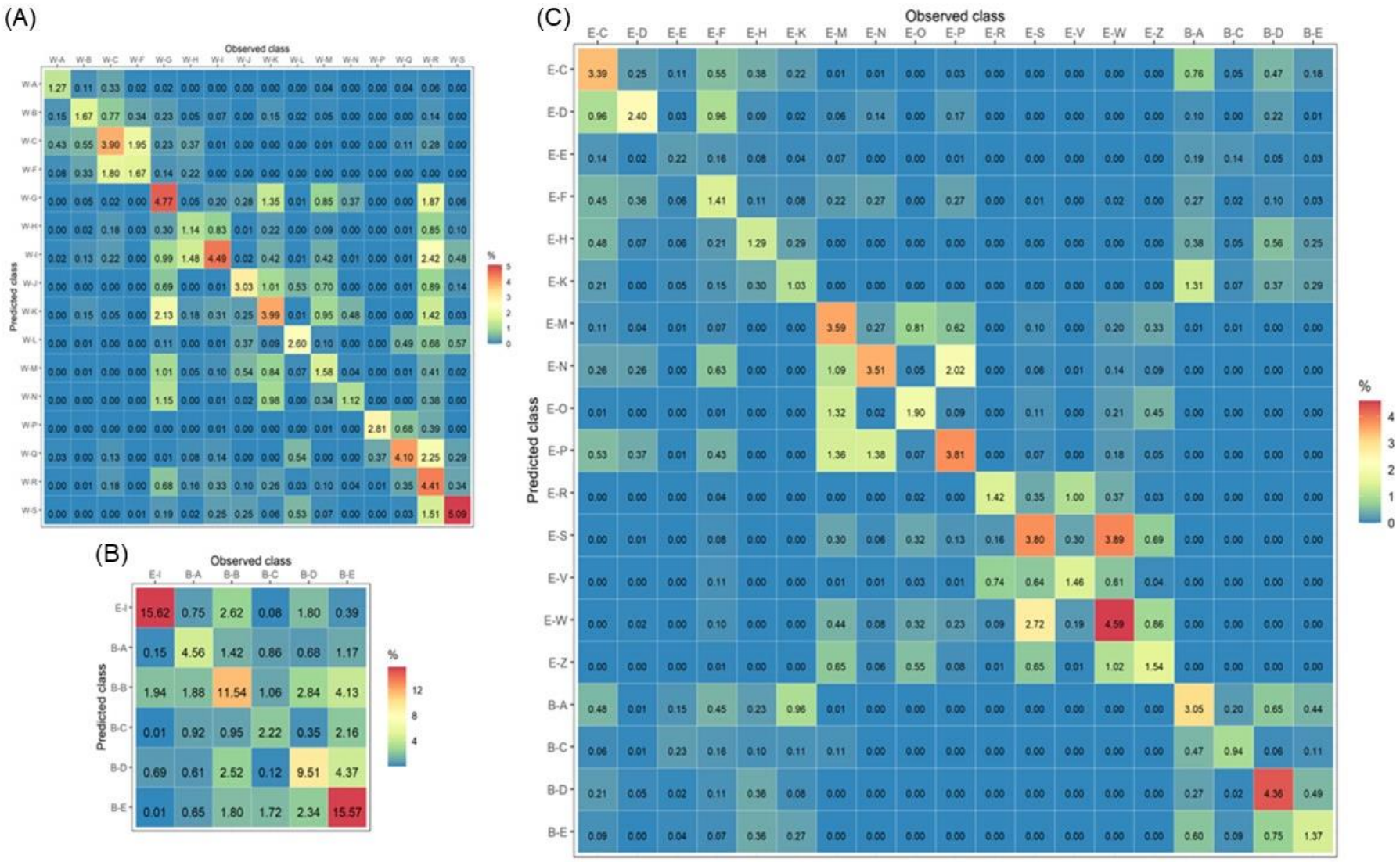
Supplementary Figure 11. Geographic distribution of predicted percent forest type of the present (2000–2019) and past (1970–1999) in the Boreal Forest biome. Percent forest type was calculated based on how many repetitions, out of 20, returned the given forest type in each grid cell (see 2.5. Forest type mapping).



Supplementary Figure 12. Performance of two candidate machine learning models to map forest types. Kappa statistic and accuracy of random forests and support-vector machine imputation models. Mean values from 20 repetitions and 95% CI are shown for each time period and arch-biome. Random forests outperformed support vector machine in all cases, and thus random forests were used to map forest types in this paper.



Supplementary Figure 13. Confusion matrix of the random forests model trained for forest type mapping using present (2000-2019) data for the (A) West, (B) East, and (C) Boreal arch-biome. The values are percent mean number of cases based on 20 repetitions.



Supplementary Figure 14. Confusion matrix of the random forests model trained for forest type mapping using past (1970-1999) data for the (A) West, (B) East, and (C) Boreal arch-biome. The values are percent mean number of cases based on 20 repetitions.

2.2 Supplementary Tables

Supplementary Table 1. Summary of the changes in tree species range. Azimuth indicates the direction of range shift, where 0° is north and 180° is south. Velocity and azimuth are not available for species with sufficient sample size in only either dataset. "W" represents West region, "E" represents East region, and "B" represents Boreal region, which indicate that the given species was included in the given forest type classification and the quantification of species range shifts due to sufficient sample size. A total of 201 species were used in the forest type classification, out of which 150 species were also used for quantifying species range shifts.

Scientific name	Common name	Present classification	Past classification	Velocity ($km \cdot decade^{-1}$)	Azimuth (°)	Area present (km^2)	Area past (km^2)	Area change (%)	Mean year present	Mean year past
Abies amabilis	Pacific silver fir	W				18476			2009	
Abies balsamea	balsam fir	EB	EB	438.61	110	292189	301107	-3	2007	1990
Abies concolor	white fir	W	W	55.54	171	17212	20375	-15.5	2009	1995
Abies grandis	grand fir	W	W	83.00	121	20876	26362	-20.8	2010	1991
Abies lasiocarpa	subalpine fir	W	W	88.79	324	117857	82848	42.3	2010	1990
Abies magnifica	California red fir	W				3394			2009	
Abies procera	noble fir	W				971			2009	
Abies shastensis	Shasta red fir	W				1698			2009	
Acer barbatum	Florida maple	E	E	148.91	295	997	387	157.6	2008	1985
Acer macrophyllum	bigleaf maple	W	W	44.63	5	5084	6369	-20.2	2009	1998
Acer negundo	boxelder	E	E	91.35	82	5020	1685	197.9	2009	1990
Acer nigrum	red maple	E	E	44.86	104	202	121	66.9	2009	1990
Acer pensylvanicum	striped maple	EB	EB	84.24	243	8702	6504	33.8	2009	1992
Acer platanoides	Norway maple	E				214			2010	
Acer rubrum	red maple	EB	EB	11.84	237	186332	170411	9.3	2008	1990
Acer saccharinum	silver maple	E	E	4.65	71	1279	1447	-11.6	2008	1990
Acer saccharum	sugar maple	EB	EB	53.93	264	107817	108165	-0.3	2008	1990
Acer spicatum	mountain maple	EB	EB	269.93	285	4879	3870	26.1	2009	1990
Aesculus flava	yellow buckeye	E				893			2008	
Aesculus glabra	Ohio buckeye	E				176			2008	
Aesculus spp.			E				934	-100	2008	1990
Ailanthus altissima	ailanthus	E	E	36.54	185	903	249	262.7	2008	1992
Albizia julibrissin	mimosa, silktree	E				193			2009	
Alnus incana	gray alder	EB	EB	354.64	108	26730	353	7472.2	2005	1991
Alnus rhombifolia	white alder	W				232			2008	
Alnus rubra	red alder	W	W	112.99	343	14604	16763	-12.9	2009	1998
Amelanchier arborea	common serviceberry	E				164			2008	
Amelanchier spp.			EB				2295	-100		1991
Arbutus menziesii	Pacific madrone	W	W	39.06	337	3490	3885	-10.2	2008	1996
Asimina triloba	pawpaw	E	E	124.01	222	1311	260	404.2	2009	1991
Betula alleghaniensis	yellow birch	EB	EB	12.48	303	41923	42480	-1.3	2007	1991
Betula lenta	sweet birch	E	E	33.84	236	13193	9635	36.9	2009	1991

Betula neoalaskana	resin birch	B				50031			2008	
Betula nigra	river birch	E	E	113.17	235	1526	1415	7.8	2008	1989
Betula papyrifera	paper birch	WEB	WEB	106.14	286	172770	189211	-8.7	2007	1990
Betula populifolia	gray birch	EB	EB	77.32	318	6306	6222	1.4	2009	1992
Calocedrus decurrens	incense cedar	W	W	31.40	161	5625	7646	-26.4	2009	1995
Carpinus caroliniana	American hornbeam, musclewood	E	E	12.30	261	11081	9029	22.7	2009	1988
Carya alba	mockernut hickory	E				13695			2008	
Carya aquatica	water hickory	E				759			2009	
Carya cordiformis	bitternut hickory	E				2506			2009	
Carya glabra	pignut hickory	E				13829			2008	
Carya illinoinensis	pecan	E				772			2009	
Carya laciniosa	shellbark hickory	E				292			2007	
Carya ovalis	red hickory	E				74			2008	
Carya ovata	shagbark hickory	E				5378			2008	
Carya pallida	sand hickory	E				166			2007	
Carya spp.			E				60049	-100	2008	1988
Carya texana	black hickory	E				5839			2009	
Castanea dentata	American chestnut	E	E	36.87	257	240	514	-53.3	2009	1991
Castanea pumila	Allegheny chinkapin		E				130	-100		1985
Celtis laevigata	sugarberry	E	E	7.25	265	4049	3564	13.6	2009	1985
Celtis occidentalis	hackberry	E	E	20.96	327	2476	2165	14.4	2008	1989
Cercis canadensis	eastern redbud	E	E	26.94	107	3030	2278	33	2008	1989
Chamaecyparis lawsoniana	Port-Orford-cedar	W				250			2009	
Chamaecyparis nootkatensis	Alaska yellow-cedar	W	W	129.37	137	16396	12152	34.9	2009	1997
Chamaecyparis thyoides	Atlantic white-cedar	E	E	177.87	223	516	562	-8.2	2010	1990
Chrysolepis chrysophylla	giant chinkapin, golden chinkapin	W	W	45.57	231	887	928	-4.4	2008	1999
Cornus florida	flowering dogwood	E	E	36.36	267	17256	33713	-48.8	2008	1988
Cornus nuttallii	Pacific dogwood	W	W	154.12	166	308	828	-62.8	2009	1996
Crataegus spp.			E				2884	-100		1989
Diospyros virginiana	common persimmon	E	E	5.76	113	4522	3999	13.1	2008	1987
Fagus grandifolia	American beech	EB	EB	51.82	259	47089	45848	2.7	2009	1991
Fraxinus americana	white ash	EB	EB	69.65	107	25077	26318	-4.7	2009	1991
Fraxinus latifolia	Oregon ash	W				423			2009	
Fraxinus nigra	black ash	EB	EB	26.17	198	15613	17284	-9.7	2008	1987
Fraxinus pennsylvanica	green ash	EB	E	144.98	18	14339	6280	128.3	2008	1987
Fraxinus quadrangulata	blue ash	E	E	72.42	191	135	76	77.6	2007	1989
Gleditsia aquatica	waterlocust		E				156	-100		1983
Gleditsia triacanthos	honeylocust	E	E	147.29	249	666	1181	-43.6	2009	1988
Gordonia lasianthus	loblolly-bay	E	E	39.20	218	1585	582	172.3	2008	1985
Halesia carolina	Carolina silverbell	E				181			2010	
Ilex opaca	American holly	E	E	52.83	248	5872	3505	67.5	2008	1989
Juglans cinerea	butternut	E	EB	199.49	165	370	501	-26.1	2010	1990
Juglans nigra	black walnut	E	E	49.13	307	3156	3371	-6.4	2009	1990
Juniperus occidentalis	western juniper	W				680			2009	

Juniperus virginiana	eastern redcedar	E	E	63.68	260	17134	12953	32.3	2008	1989
Larix laricina	tamarack	EB	EB	106.00	105	66864	39563	69	2009	1988
Larix occidentalis	western larch	W	W	120.22	126	14596	29500	-50.5	2010	1990
Liquidambar styraciflua	sweetgum	E	E	4.51	25	70362	68072	3.4	2008	1987
Liriodendron tulipifera	yellow-poplar	E	E	20.91	234	38815	32287	20.2	2008	1990
Lithocarpus densiflorus	tanoak	W	W	44.47	338	7043	7766	-9.3	2009	1995
Maclura pomifera	Osage-orange	E	E	12.97	1	452	493	-8.3	2009	1989
Magnolia acuminata	cucumbertree	E	E	23.17	29	988	1175	-15.9	2009	1989
Magnolia fraseri	mountain or Fraser magnolia	E				487			2009	
Magnolia grandiflora	southern magnolia	E	E	36.67	259	494	589	-16.1	2009	1984
Magnolia macrophylla	bigleaf magnolia	E	E	31.01	74	241	174	38.5	2007	1985
Magnolia tripetala	umbrella magnolia	E				117			2008	
Magnolia virginiana	sweetbay	E	E	21.90	305	5793	5194	11.5	2009	1983
Malus spp.			E				2164	-100		1992
Melia azedarach	chinaberry	E				707			2008	
Morus alba	white mulberry	E	E	263.82	37	146	140	4.3	2009	1988
Morus rubra	red mulberry	E	E	53.66	336	772	1187	-35	2008	1987
Nyssa aquatica	water tupelo	E	E	19.14	34	3422	3238	5.7	2008	1984
Nyssa biflora	swamp tupelo	E	E	23.18	264	8764	11143	-21.3	2008	1985
Nyssa sylvatica	blackgum	E	E	29.09	27	26474	28080	-5.7	2008	1988
Ostrya virginiana	eastern hophornbeam	EB	EB	119.22	250	15447	11985	28.9	2008	1989
Oxydendrum arboreum	sourwood	E	E	9.28	273	11043	10771	2.5	2007	1988
Paulownia tomentosa	paulownia, empress-tree	E				279			2008	
Persea borbonia	redbay	E	E	83.00	72	3022	1425	112.1	2008	1988
Picea abies	Norway spruce	E	E	142.54	57	2232	770	189.9	2009	1992
Picea engelmannii	Engelmann spruce	W	W	29.75	347	73490	60376	21.7	2010	1990
Picea glauca	white spruce	WEB	EB	81.13	271	279390	343018	-18.5	2007	1991
Picea mariana	black spruce	EB	EB	159.16	290	916839	698589	31.2	2007	1990
Picea pungens	blue spruce	W				464			2010	
Picea rubens	red spruce	EB	EB	19.57	172	27680	29690	-6.8	2008	1992
Picea sitchensis	Sitka spruce	W	W	480.43	294	22718	66366	-65.8	2009	1998
Pinus albicaulis	whitebark pine	W	W	164.80	132	7921	17909	-55.8	2010	1989
Pinus attenuata	knobcone pine	W				230			2009	
Pinus banksiana	jack pine	EB	EB	34.47	119	244596	362489	-32.5	2008	1989
Pinus clausa	sand pine	E	E	16.16	21	1664	1397	19.1	2010	1978
Pinus contorta	lodgepole pine	WB	WB	63.60	321	186644	164058	13.8	2010	1990
Pinus echinata	shortleaf pine	E	E	46.27	331	17397	41326	-57.9	2009	1985
Pinus elliottii	slash pine	E	E	9.86	134	32492	36200	-10.2	2009	1983
Pinus flexilis	limber pine	W	W	215.45	133	2335	5677	-58.9	2010	1990
Pinus glabra	spruce pine	E	E	19.89	261	358	612	-41.5	2008	1984
Pinus jeffreyi	Jeffrey pine	W				1918			2009	
Pinus lambertiana	sugar pine	W	W	22.96	170	2227	2377	-6.3	2009	1994
Pinus monticola	western white pine	W	W	57.21	151	3216	6498	-50.5	2009	1991
Pinus palustris	longleaf pine	E	E	14.61	79	8086	13992	-42.2	2009	1982
Pinus ponderosa	ponderosa pine	W	W	18.96	20	34363	35977	-4.5	2009	1995

Pinus pungens	Table Mountain pine	E	E	45.37	44	198	289	-31.5	2009	1992
Pinus resinosa	red pine	EB	EB	63.39	260	12217	16799	-27.3	2008	1989
Pinus rigida	pitch pine	E	E	11.61	235	3788	3829	-1.1	2011	1993
Pinus serotina	pond pine	E	E	54.33	33	1693	4372	-61.3	2008	1980
Pinus strobiformis	southwestern white pine	W	W	87.34	98	409	380	7.6	2011	1998
Pinus strobus	eastern white pine	EB	EB	26.11	211	43500	36299	19.8	2008	1991
Pinus sylvestris	Scotch pine	E	E	60.72	72	1719	1231	39.6	2008	1990
Pinus taeda	loblolly pine	E	E	24.24	252	170427	130991	30.1	2008	1987
Pinus virginiana	Virginia pine	E	E	9.01	222	12418	15752	-21.2	2007	1989
Planera aquatica	water-elm, planertree	E	E	4.47	201	755	655	15.3	2011	1985
Platanus occidentalis	American sycamore	E	E	13.05	212	3193	2851	12	2008	1990
Populus balsamifera	balsam poplar	WEB	WEB	79.63	288	56050	72926	-23.1	2008	1987
Populus deltoides	eastern cottonwood	E	E	127.68	173	521	590	-11.7	2008	1992
Populus grandidentata	bigtooth aspen	EB	EB	40.70	237	9922	15193	-34.7	2007	1989
Populus tremuloides	quaking aspen	WEB	WEB	52.86	124	349704	451892	-22.6	2008	1988
Prunus americana	American plum	E	E	304.82	127	199	109	82.6	2009	1992
Prunus avium	sweet cherry, domesticated	E				176			2011	
Prunus emarginata	bitter cherry	W				450			2009	
Prunus pensylvanica	pin cherry	EB	EB	229.75	108	7453	10203	-27	2007	1991
Prunus serotina	black cherry	EB	EB	121.26	176	33953	28780	18	2009	1990
Prunus virginiana	chokecherry	E	E	70.33	166	810	1131	-28.4	2009	1990
Pseudotsuga menziesii	Douglas-fir	W	W	5.91	13	152114	141947	7.2	2009	1993
Quercus agrifolia	California live oak	W				1309			2009	
Quercus alba	white oak	E	E	14.46	260	52860	60382	-12.5	2008	1989
Quercus bicolor	swamp white oak	E	E	113.59	1	141	571	-75.3	2008	1990
Quercus chrysolepis	canyon live oak	W	W	17.51	317	5678	3476	63.3	2009	1994
Quercus coccinea	scarlet oak	E	E	16.25	89	10365	13617	-23.9	2008	1990
Quercus ellipsoidalis	northern pin oak	E	E	28.07	96	2180	1159	88.1	2008	1987
Quercus falcata	southern red oak	E	E	22.32	48	12897	17898	-27.9	2008	1986
Quercus garryana	Oregon white oak	W	W	68.44	357	988	2898	-65.9	2009	1997
Quercus ilicifolia	scrub oak	E				481			2010	
Quercus imbricaria	shingle oak	E	E	45.79	259	596	511	16.6	2008	1990
Quercus incana	bluejack oak	E				260			2009	
Quercus kelloggii	California black oak	W	W	25.23	145	3880	5402	-28.2	2009	1995
Quercus laevis	turkey oak	E	E	41.44	12	496	1527	-67.5	2008	1986
Quercus laurifolia	laurel oak	E	E	16.13	281	9022	7464	20.9	2008	1985
Quercus lyrata	overcup oak	E	E	19.62	304	1571	2355	-33.3	2009	1984
Quercus macrocarpa	bur oak	E	E	13.90	353	2225	2100	6	2009	1986
Quercus margarettiae	dwarf post oak	E	E	99.82	151	278	485	-42.7	2007	1986
Quercus marilandica	blackjack oak	E	E	56.62	286	2015	5141	-60.8	2009	1987
Quercus michauxii	swamp chestnut oak	E	E	56.05	49	325	968	-66.4	2008	1986
Quercus muehlenbergii	chinkapin oak	E	E	40.85	99	2218	1477	50.2	2008	1989
Quercus nigra	water oak	E	E	30.13	258	32552	25384	28.2	2008	1986
Quercus pagoda	cherrybark oak	E	E	5.98	318	2756	3736	-26.2	2009	1985
Quercus palustris	pin oak	E	E	53.46	301	477	723	-34	2009	1991
Quercus phellos	willow oak	E	E	38.46	61	3437	4605	-25.4	2009	1986

Quercus prinus	chestnut oak	E	E	33.58	233	23140	26463	-12.6	2008	1990
Quercus rubra	northern red oak	EB	EB	25.54	331	38190	40168	-4.9	2008	1989
Quercus shumardii	Shumard oak	E	E	147.91	336	304	210	44.8	2009	1986
Quercus stellata	post oak	E	E	17.93	16	18752	25653	-26.9	2009	1987
Quercus texana	Texas red oak	E	E	17.09	43	1082	800	35.3	2010	1983
Quercus velutina	black oak	E	E	21.80	29	23232	30604	-24.1	2008	1989
Quercus virginiana	live oak	E	E	56.43	274	2931	2117	38.5	2009	1981
Quercus wislizeni	interior live oak	W				725			2008	
Robinia pseudoacacia	black locust	E	E	29.52	289	7976	6916	15.3	2009	1990
Sabal palmetto	cabbage palmetto	E	E	12.05	52	1426	924	54.3	2010	1983
Salix amygdaloides	peachleaf willow	E				229			2008	
Salix bebbiana	Bebb willow	E				172			2009	
Salix nigra	black willow	E				2788			2009	
Salix spp.			EB				13358	-100	2009	1989
Sassafras albidum	sassafras	E	E	9.14	256	8784	10512	-16.4	2008	1989
Sequoia sempervirens	redwood	W	W	13.40	233	3715	4319	-14	2009	1994
Sideroxylon lanuginosum	chittamwood, gum bumelia	E	E	14.67	274	129	129	0	2010	1986
Sorbus americana	American mountain-ash	EB	EB	210.61	113	2058	2428	-15.2	2007	1991
Taxodium ascendens	pondcypress	E	E	1.46	54	3781	5628	-32.8	2009	1980
Taxodium distichum	baldcypress	E	E	16.36	314	4707	4057	16	2009	1983
Taxus brevifolia	Pacific yew	W				1036			2010	
Thuja occidentalis	northern white-cedar	EB	EB	87.40	295	53848	48133	11.9	2007	1990
Thuja plicata	western redcedar	W	W	12.69	231	27636	26033	6.2	2010	1993
Tilia americana	American basswood	EB	EB	100.79	143	8411	9726	-13.5	2008	1988
Triadica sebifera	Chinese tallowtree	E				2362			2009	
Tsuga canadensis	eastern hemlock	EB	EB	42.20	266	33125	26553	24.8	2009	1991
Tsuga heterophylla	western hemlock	W	W	71.56	190	76392	88023	-13.2	2009	1996
Tsuga mertensiana	mountain hemlock	W	W	71.49	323	41475	40106	3.4	2009	1996
Ulmus alata	winged elm	E	E	37.75	74	15196	10369	46.6	2009	1987
Ulmus americana	American elm	EB	EB	52.61	191	13637	14485	-5.9	2009	1988
Ulmus crassifolia	cedar elm	E	E	101.74	245	498	539	-7.6	2009	1984
Ulmus rubra	slippery elm	E	E	30.63	231	3881	3975	-2.4	2008	1989
Ulmus thomasii	rock elm	E	E	120.45	352	94	388	-75.8	2008	1988
Umbellularia californica	California-laurel	W	W	32.04	170	1674	1729	-3.2	2009	1995

Supplementary Table 2. List of predictor variables used to model range shift of forest types and tree species.

Variable	Definition (unit)	1970-1999			2000-2019		
		Data source	Reference year	Resolution	Data source	Reference year	Resolution
Climate covariates							
C1	Annual mean temperature (0.1 °C)	WorldClim v.2.1 (Fick and Hijmans, 2017)	1970-2000	1 km^2	CHELSA v.1.2 (Karger et al., 2022, Karger et al., 2017)	1979-2013	1 km^2
C2	Mean diurnal range (°C)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C3	Isothermality (unitless*100)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C4	Temperature seasonality (standard deviation*100)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C5	Temperature annual range (0.1 °C)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C6	Mean temperature of wettest quarter (0.1 °C)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C7	Mean temperature of driest quarter (0.1 °C)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C8	Mean temperature of warmest quarter (0.1 °C)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C9	Mean temperature of coldest quarter (0.1 °C)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C10	Annual precipitation (mm)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C11	Precipitation seasonality (coefficient of variation)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C12	Precipitation of wettest quarter (mm)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C13	Precipitation of driest quarter (mm)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C14	Precipitation of warmest quarter (mm)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C15	Precipitation of coldest quarter (mm)	WorldClim v.2.1	1970-2000	1 km^2	CHELSA v.1.2	1979-2013	1 km^2
C16	Potential evapotranspiration (mm $year^{-1}$)	CGIAR-CSI v.2 (Trabucco and Zomer, 2019)	1970-2000	1 km^2	CGIAR-CSI v.2	1970-2000	1 km^2
C17	Indexed annual aridity (unitless index*10^{-4})	CGIAR-CSI v.2	1970-2000	1 km^2	CGIAR-CSI v.2	1970-2000	1 km^2
Topographic covariates							
T1	Elevation (m)	EarthEnv (Amatulli et al., 2018)	2010	1 km^2	EarthEnv	2010	1 km^2
T2	Roughness	EarthEnv	2010	1 km^2	EarthEnv	2010	1 km^2
T3	Terrain ruggedness index	EarthEnv	2010	1 km^2	EarthEnv	2010	1 km^2
T4	Topographic position index	EarthEnv	2010	1 km^2	EarthEnv	2010	1 km^2
T5	Aspect cosine	EarthEnv	2010	1 km^2	EarthEnv	2010	1 km^2
T6	Aspect sine	EarthEnv	2010	1 km^2	EarthEnv	2010	1 km^2
T7	Slope	EarthEnv	2010	1 km^2	EarthEnv	2010	1 km^2
T8	Profile curvature	EarthEnv	2010	1 km^2	EarthEnv	2010	1 km^2
T9	Tangential curvature	EarthEnv	2010	1 km^2	EarthEnv	2010	1 km^2
T10	First order partial derivative (E-W slope)	EarthEnv	2010	1 km^2	EarthEnv	2010	1 km^2
T11	First order partial derivative (N-S slope)	EarthEnv	2010	1 km^2	EarthEnv	2010	1 km^2
T12	Second order partial derivative (E-W slope)	EarthEnv	2010	1 km^2	EarthEnv	2010	1 km^2
T13	Second order partial derivative (N-S slope)	EarthEnv	2010	1 km^2	EarthEnv	2010	1 km^2
Soil covariates							
S1	Bulk density (g cm^{-3})	WISE30sec v1.0 (Batjes, 2016)	na	1 km^2	WISE30sec v1.0	na	1 km^2
S2	Percent clay (mass %)	WISE30sec v1.0	na	1 km^2	WISE30sec v1.0	na	1 km^2

S3	Organic carbon content (g kg^{-1})	WISE30sec v1.0	na	1 km^2	WISE30sec v1.0	na	1 km^2
S4	pH measured in water	WISE30sec v1.0	na	1 km^2	WISE30sec v1.0	na	1 km^2
S5	Electrical conductivity (dS m^{-1})	WISE30sec v1.0	na	1 km^2	WISE30sec v1.0	na	1 km^2
S6	C/N ratio	WISE30sec v1.0	na	1 km^2	WISE30sec v1.0	na	1 km^2
S7	Total nitrogen (g kg^{-1})	WISE30sec v1.0	na	1 km^2	WISE30sec v1.0	na	1 km^2
Anthropogenic impact							
H	Human footprint	(Venter et al., 2016)	1993	1 km^2	(Venter et al., 2016)	2009	1 km^2

Supplementary Table 3. Summary of forest types and forest biomes classified based on the present (2000–2019) and past (1970–1999) forest inventories. Only the top dominant species in terms of species cumulative relative abundance ($\boldsymbol{p_i}$) in each forest type are listed to save space. Forest types with "W-" belong to the West arch-biome, "E-" to the East arch-biome, and "B-" to the Boreal arch-biome. A total of 51 forest types were identified, of which 43 forest types were present in both present and past periods.

Forest biome (present area km^2)	Forest type	Forest type name	Time	Area (km^2)	Constituent species (p_i)
Pacific Coastal Forest (249,806)	W-A	Sitka spruce—western hemlock	present	12,959	*Picea sitchensis* (0.57), *Tsuga heterophylla* (0.15), *Tsuga mertensiana* (0.10), *Populus balsamifera* (0.06)
			past	28,469	*Picea sitchensis* (0.40), *Tsuga heterophylla* (0.18), *Tsuga mertensiana* (0.11), *Pinus contorta* (0.06)
	W-B	mountain hemlock—cedar—spruce	present	49,228	*Tsuga mertensiana* (0.37), *Tsuga heterophylla* (0.20), *Picea sitchensis* (0.10)
			past	54,883	*Tsuga mertensiana* (0.25), *Tsuga heterophylla* (0.21), *Picea sitchensis* (0.17), *Pinus contorta* (0.07)
	W-C	western hemlock—cedar—spruce	present	120,070	*Tsuga heterophylla* (0.35), *Pseudotsuga menziesii* (0.13), *Thuja plicata* (0.10)
			past	124,151	*Tsuga heterophylla* (0.29), *Picea sitchensis* (0.14), *Tsuga mertensiana* (0.12)
	W-D	red alder—Douglas-fir	present	41,085	*Pseudotsuga menziesii* (0.47), *Alnus rubra* (0.16), *Tsuga heterophylla* (0.11), *Thuja plicata* (0.07)
			past	30,329	*Pseudotsuga menziesii* (0.42), *Alnus rubra* (0.19), *Tsuga heterophylla* (0.13), *Acer macrophyllum* (0.07)
	W-E	fir—hemlock	present	26,463	*Abies amabilis* (0.29), *Tsuga heterophylla* (0.19), *Pseudotsuga menziesii* (0.17)
	W-F	yellow-cedar—hemlock	past	10,522	*Tsuga heterophylla* (0.37), *Chamaecyparis nootkatensis* (0.24), *Tsuga mertensiana* (0.15)
Western Cordillera (502,547)	W-G	mixed lodgepole pine forest	present	124,573	*Pinus contorta* (0.39), *Abies lasiocarpa* (0.17), *Picea engelmannii* (0.15), *Pseudotsuga menziesii* (0.12)
			past	100,961	*Pinus contorta* (0.31), *Picea engelmannii* (0.13), *Abies lasiocarpa* (0.13), *Pseudotsuga menziesii* (0.10)
	W-H	Northern Rocky Mountains cedar—larch—hemlock	present	33,435	*Pseudotsuga menziesii* (0.27), *Thuja plicata* (0.12), *Pinus contorta* (0.12), *Larix occidentalis* (0.09)
			past	24,925	*Pseudotsuga menziesii* (0.22), *Thuja plicata* (0.12), *Tsuga heterophylla* (0.12), *Abies grandis* (0.11)
	W-I	grand fir—Douglas-fir	present	47,490	*Pseudotsuga menziesii* (0.30), *Abies grandis* (0.26), *Pinus contorta* (0.09), *Pinus ponderosa* (0.08)
			past	40,029	*Pseudotsuga menziesii* (0.28), *Abies grandis* (0.23), *Pinus contorta* (0.10), *Pinus ponderosa* (0.09)
	W-J	aspen-mixed conifer	present	31,435	*Populus tremuloides* (0.26), *Abies lasiocarpa* (0.16), *Pinus contorta* (0.12), *Pseudotsuga menziesii* (0.11)
			past	25,466	*Populus tremuloides* (0.33), *Pseudotsuga menziesii* (0.15), *Pinus contorta* (0.13), *Abies lasiocarpa* (0.12)
	W-K	subalpine fir—lodgepole pine	present	203,700	*Abies lasiocarpa* (0.36), *Pinus contorta* (0.20), *Picea engelmannii* (0.18), *Pseudotsuga menziesii* (0.07)
			past	155,666	*Abies lasiocarpa* (0.36), *Pinus contorta* (0.18), *Picea engelmannii* (0.13), *Picea sitchensis* (0.09)
	W-L	white fir—Douglas-fir—ponderosa pine	present	27,668	*Abies concolor* (0.38), *Pseudotsuga menziesii* (0.11), *Abies magnifica* (0.11), *Pinus ponderosa* (0.10)
			past	35,361	*Abies concolor* (0.35), *Pseudotsuga menziesii* (0.18), *Pinus ponderosa* (0.15)
	W-M	Engelmann spruce—subalpine fir	present	34,246	*Picea engelmannii* (0.29), *Abies lasiocarpa* (0.24), *Pinus contorta* (0.21), *Populus tremuloides* (0.07)
			past	62,889	*Pinus contorta* (0.22), *Picea engelmannii* (0.21), *Abies lasiocarpa* (0.16), *Populus tremuloides* (0.09)
	W-N	lodgepole pine—subalpine fir—whitebark	past	12,349	*Pinus contorta* (0.29), *Abies lasiocarpa* (0.22), *Pinus albicaulis* (0.19), *Picea engelmannii* (0.12)
	W-O	lodgepole pine—Douglas-fir—western larch	past	40,745	*Pseudotsuga menziesii* (0.20), *Pinus contorta* (0.18), *Larix occidentalis* (0.10), *Abies lasiocarpa* (0.09)
Mediterranean California (59,849)	W-P	coastal redwood—tanoak	present	23,266	*Pseudotsuga menziesii* (0.32), *Lithocarpus densiflorus* (0.25), *Sequoia sempervirens* (0.15)
			past	18,271	*Lithocarpus densiflorus* (0.30), *Pseudotsuga menziesii* (0.26), *Sequoia sempervirens* (0.19)
	W-Q	California mixed oak woodland	present	36,583	*Pseudotsuga menziesii* (0.31), *Quercus chrysolepis* (0.12), *Pinus ponderosa* (0.11)
			past	52,385	*Pseudotsuga menziesii* (0.36), *Quercus kelloggii* (0.08), *Pinus ponderosa* (0.07)
Coastal-Interior Range (65,438)	W-R	Douglas-fir mixed forest	present	34,915	*Pseudotsuga menziesii* (0.60), *Tsuga heterophylla* (0.06), *Pinus contorta* (0.05), *Pinus ponderosa* (0.05)
			past	32,276	*Pseudotsuga menziesii* (0.57), *Pinus contorta* (0.07), *Tsuga heterophylla* (0.07), *Pinus ponderosa* (0.05)
	W-S	ponderosa pine—fir	present	30,524	*Pinus ponderosa* (0.48), *Pseudotsuga menziesii* (0.26), *Abies grandis* (0.06), *Abies concolor* (0.05)
			past	27,961	*Pinus ponderosa* (0.49), *Pseudotsuga menziesii* (0.22), *Abies concolor* (0.07), *Pinus contorta* (0.06)
Eastern Mixed Forest (644,011)	E-A	red oak mixed hardwood forest	present	56,652	*Acer rubrum* (0.17), *Acer saccharum* (0.10), *Quercus rubra* (0.07), *Prunus serotina* (0.06)
			past	46,698	*Populus tremuloides* (0.15), *Acer rubrum* (0.13), *Quercus rubra* (0.10), *Populus grandidentata* (0.07)

	E-B	Great Lakes tamarack—spruce	present	10,091	*Larix laricina* (0.27), *Picea mariana* (0.18), *Populus tremuloides* (0.13), *Thuja occidentalis* (0.09)
			past	7,987	*Larix laricina* (0.19), *Populus tremuloides* (0.14), *Picea mariana* (0.14), *Abies balsamea* (0.09)
	E-C	North-central maple forest	present	80,059	*Acer saccharum* (0.24), *Abies balsamea* (0.11), *Acer rubrum* (0.10), *Populus tremuloides* (0.06)
			past	49,747	*Acer saccharum* (0.26), *Acer rubrum* (0.11), *Abies balsamea* (0.09), *Populus tremuloides* (0.09)
	E-D	beech—maple	present	50,902	*Fagus grandifolia* (0.19), *Acer rubrum* (0.15), *Acer saccharum* (0.14), *Betula alleghaniensis* (0.07)
			past	104,869	*Acer rubrum* (0.15), *Acer saccharum* (0.13), *Fagus grandifolia* (0.13), *Abies balsamea* (0.06)
	E-E	Great Lakes pine forest	present	22,786	*Pinus resinosa* (0.12), *Populus tremuloides* (0.12), *Pinus banksiana* (0.11), *Acer rubrum* (0.10)
			past	10,353	*Pinus resinosa* (0.14), *Populus tremuloides* (0.13), *Acer rubrum* (0.10), *Acer saccharum* (0.06)
	E-F	red maple—hardwood	present	46,720	*Acer rubrum* (0.29), *Acer saccharum* (0.07), *Quercus rubra* (0.05), *Prunus serotina* (0.05)
			past	61,350	*Acer rubrum* (0.26), *Acer saccharum* (0.08), *Quercus rubra* (0.05), *Prunus serotina* (0.05)
	E-G	maple—eastern hemlock	present	49,452	*Acer rubrum* (0.18), *Tsuga canadensis* (0.14), *Acer saccharum* (0.09), *Pinus strobus* (0.09)
			past	27,402	*Acer rubrum* (0.18), *Tsuga canadensis* (0.12), *Acer saccharum* (0.11), *Pinus strobus* (0.07)
	E-H	balsam fir—northern white-cedar	present	28,370	*Abies balsamea* (0.18), *Thuja occidentalis* (0.17), *Acer rubrum* (0.10), *Populus tremuloides* (0.08)
			past	37,928	*Thuja occidentalis* (0.16), *Abies balsamea* (0.16), *Acer rubrum* (0.10), *Populus tremuloides* (0.09)
	E-I	balsam fir—maple—birch	present	229,088	*Abies balsamea* (0.18), *Acer rubrum* (0.10), *Acer saccharum* (0.09), *Betula alleghaniensis* (0.07)
			past	264,717	*Abies balsamea* (0.16), *Acer saccharum* (0.11), *Acer rubrum* (0.10), *Betula papyrifera* (0.08)
	E-J	eastern white pine—maple	present	37,905	*Acer rubrum* (0.21), *Pinus strobus* (0.19), *Quercus rubra* (0.07), *Tsuga canadensis* (0.07)
			past	38,080	*Pinus strobus* (0.20), *Acer rubrum* (0.20), *Tsuga canadensis* (0.08), *Quercus rubra* (0.07)
	E-K	Great Lakes poplar—black ash	present	9,842	*Populus tremuloides* (0.18), *Fraxinus nigra* (0.11), *Acer rubrum* (0.10), *Abies balsamea* (0.09)
			past	17,210	*Populus tremuloides* (0.25), *Fraxinus nigra* (0.11), *Abies balsamea* (0.11), *Betula papyrifera* (0.08)
	E-L	maple—black cherry	present	22,143	*Acer rubrum* (0.21), *Prunus serotina* (0.18), *Acer saccharum* (0.08), *Quercus rubra* (0.05)
Central Forest (414,850)	E-M	white oak—hickory	present	58,484	*Quercus alba* (0.14), *Acer rubrum* (0.07), *Quercus velutina* (0.05), *Liriodendron tulipifera* (0.05)
			past	62,119	*Quercus alba* (0.17), *Carya* spp. (0.12), *Quercus velutina* (0.10), *Cornus florida* (0.06)
	E-N	Appalachian oak–pine	present	93,250	*Acer rubrum* (0.14), *Quercus prinus* (0.12), *Quercus alba* (0.06), *Liriodendron tulipifera* (0.06)
			past	120,228	*Acer rubrum* (0.14), *Quercus prinus* (0.11), *Quercus alba* (0.07), *Carya* spp. (0.06)
	E-O	mixed oak—hickory	present	78,024	Quercus stellata (0.12), Quercus alba (0.11), Pinus echinata (0.10), Quercus velutina (0.07)
			past	49,986	*Quercus stellata* (0.17), *Carya* spp. (0.12), *Quercus velutina* (0.11), *Quercus alba* (0.09)
	E-P	maple—yellow-poplar	present	112,098	*Acer rubrum* (0.13), *Liriodendron tulipifera* (0.12), *Acer saccharum* (0.08), *Quercus alba* (0.06)
			past	112,147	*Acer rubrum* (0.10), *Liriodendron tulipifera* (0.10), *Carya* spp. (0.08), *Acer saccharum* (0.07)
	E-Q	eastern redcedar—maple—oak	present	72,994	*Acer saccharum* (0.09), *Juniperus virginiana* (0.08), *Quercus alba* (0.07), *Acer rubrum* (0.05)
			past	68,975	*Carya* spp. (0.08), *Acer saccharum* (0.08), *Acer rubrum* (0.07), *Quercus alba* (0.06)
Southeastern Plains (547,118)	E-R	slash pine mixed	present	49,073	*Pinus elliottii* (0.43), *Pinus taeda* (0.12), *Nyssa biflora* (0.05), *Quercus nigra* (0.05)
			past	44,838	*Pinus elliottii* (0.44), *Pinus taeda* (0.09), *Nyssa biflora* (0.07), *Pinus palustris* (0.06)
	E-S	loblolly pine—sweetgum	present	118,746	*Pinus taeda* (0.46), *Liquidambar styraciflua* (0.13), *Quercus nigra* (0.07), *Acer rubrum* (0.05)
			past	150,713	*Pinus taeda* (0.37), *Liquidambar styraciflua* (0.14), *Pinus echinata* (0.06), *Quercus nigra* (0.05)
	E-T	green ash-mixed floodplain forest	present	47,788	*Pinus taeda* (0.13), *Liquidambar styraciflua* (0.10), *Fraxinus pennsylvanica* (0.08), *Celtis laevigata* (0.06)
			past	54,381	*Pinus taeda* (0.12), *Liquidambar styraciflua* (0.12), *Carya* spp. (0.07), *Fraxinus pennsylvanica* (0.05)
	E-U	longleaf mixed pine	present	18,482	*Pinus taeda* (0.22), *Pinus palustris* (0.15), *Pinus elliottii* (0.13), *Quercus nigra* (0.08)
			past	20,539	*Pinus palustris* (0.20), *Pinus elliottii* (0.16), *Pinus taeda* (0.14), *Liquidambar styraciflua* (0.05)
	E-V	southern lowland mixed forest	present	57,916	*Pinus taeda* (0.21), *Pinus elliottii* (0.12), *Acer rubrum* (0.09), *Liquidambar styraciflua* (0.07)
			past	70,701	*Pinus taeda* (0.17), *Pinus elliottii* (0.14), *Acer rubrum* (0.08), *Liquidambar styraciflua* (0.08)
	E-W	loblolly pine—sweetgum—water oak	present	131,721	*Pinus taeda* (0.31), *Liquidambar styraciflua* (0.17), *Quercus nigra* (0.07), *Acer rubrum* (0.06)
			past	134,061	*Pinus taeda* (0.25), *Liquidambar styraciflua* (0.16), *Pinus echinata* (0.07), *Acer rubrum* (0.05)
	E-X	Virginia pine—maple	present	38,640	*Acer rubrum* (0.11), *Pinus taeda* (0.10), *Pinus virginiana* (0.10), *Liriodendron tulipifera* (0.09)
			past	43,042	*Pinus virginiana* (0.13), *Acer rubrum* (0.09), *Quercus alba* (0.09), *Liriodendron tulipifera* (0.07)
	E-Y	loblolly pine—sweetgum mixed	present	84,752	*Pinus taeda* (0.38), *Liquidambar styraciflua* (0.14), *Quercus nigra* (0.06), *Acer rubrum* (0.06)

	E-Z	shortleaf–loblolly pine	past	55,820	*Pinus echinata* (0.21), *Pinus taeda* (0.15), *Liquidambar styraciflua* (0.09), *Carya* spp. (0.08)
Boreal Forest (2,462,924)	B-A	quaking aspen—spruce	present	349,949	*Populus tremuloides* (0.26), *Picea mariana* (0.23), *Pinus banksiana* (0.11), *Picea glauca* (0.10)
			past	1,104,633	*Picea glauca* (0.24), *Populus tremuloides* (0.21), *Picea mariana* (0.17), *Pinus banksiana* (0.12)
	B-B	paper birch—balsam fir	present	153,236	*Abies balsamea* (0.22), *Betula papyrifera* (0.16), *Picea mariana* (0.16), *Populus tremuloides* (0.08)
			past	123,495	*Betula papyrifera* (0.21), *Picea mariana* (0.17), *Abies balsamea* (0.16), *Populus tremuloides* (0.10)
	B-C	black spruce—jack pine	present	294,291	*Picea mariana* (0.40), *Pinus banksiana* (0.27), *Populus tremuloides* (0.14), *Betula papyrifera* (0.05)
			past	527,541	*Pinus banksiana* (0.32), *Picea mariana* (0.31), *Populus tremuloides* (0.19), *Picea glauca* (0.06)
	B-D	balsam fir—black spruce	present	200,950	*Abies balsamea* (0.33), *Picea mariana* (0.25), *Betula papyrifera* (0.08), *Picea glauca* (0.07)
			past	222,889	*Abies balsamea* (0.33), *Picea mariana* (0.27), *Betula papyrifera* (0.09), *Picea glauca* (0.08)
	B-E	black spruce—balsam fir	present	750,121	*Picea mariana* (0.59), *Abies balsamea* (0.10), *Pinus banksiana* (0.10), *Populus tremuloides* (0.06)
			past	436,470	*Picea mariana* (0.57), *Abies balsamea* (0.14), *Pinus banksiana* (0.11), *Populus tremuloides* (0.05)
	B-F	black spruce—white spruce	present	714,379	*Picea mariana* (0.26), *Picea glauca* (0.24), *Populus tremuloides* (0.14), *Pinus contorta* (0.08)

Supplementary Table 4. Summary of range shift patterns of forest types, tree species, and covariance for each forest type. Based on the latitudinal and longitudinal shift, kilometer-based distance was calculated using past forest type centroid (see 2. Materials and methods). Thus, the sum of species-level shift and covariance matches forest type shift in the respective latitudinal and longitudinal gradient, but the sum of species shift distance in kilometer and covariance does not necessarily equal the forest type distance shift. Azimuth indicates the direction of shift, where 0° is north and 180° is south. Velocity and azimuth are not available for forest types that are present only for one time period.

Forest Type	Silhouette width present (mean±95%CI)	Silhouette width past (mean±95%CI)	Forest type shift		Velocity of tree species (km·decade^{-1})	Velocity of covariance (km·decade^{-1})	Latitudinal shift (°·decade^{-1})			Longitudinal shift (°·decade^{-1})		
			Velocity (km·decade^{-1})	Azimuth (°)			Forest type	Species	Covariance	Forest type	Species	Covariance
W-A	0.52±0.00	0.63±0.00	327.79	299.52	214.61	122.40	1.450	0.701	0.749	-4.329	-2.988	-1.341
W-B	0.35±0.00	0.54±0.00	141.50	307.26	70.54	76.15	0.769	0.241	0.528	-1.673	-0.959	-0.714
W-C	0.35±0.00	0.47±0.00	42.75	240.91	46.22	22.35	-0.186	-0.002	-0.184	-0.540	-0.669	0.130
W-D	0.10±0.00	0.28±0.02	43.79	45.97	25.99	53.74	0.273	0.147	0.127	0.424	-0.272	0.695
W-E	0.33±0.00											
W-F		0.38±0.00										
W-G	0.55±0.00	0.58±0.01	9.93	12.82	40.15	35.37	0.087	0.271	-0.184	0.032	-0.382	0.414
W-H	0.13±0.02	0.23±0.01	22.68	117.22	1.00	23.03	-0.093	-0.006	-0.087	0.279	-0.010	0.289
W-I	0.33±0.04	0.32±0.03	18.34	111.56	17.76	0.84	-0.060	-0.053	-0.007	0.229	0.225	0.004
W-J	0.42±0.02	0.53±0.00	48.11	339.92	14.43	34.64	0.406	0.103	0.303	-0.240	-0.126	-0.113
W-K	0.30±0.01	0.37±0.01	28.79	54.15	44.42	56.14	0.151	0.292	-0.141	0.336	-0.436	0.771
W-L	0.33±0.03	0.36±0.01	48.16	183.27	19.92	30.18	-0.433	-0.172	-0.261	-0.034	0.070	-0.104
W-M	0.29±0.00	0.28±0.02	23.89	44.80	35.09	39.96	0.152	0.250	-0.097	0.242	-0.308	0.550
W-N		0.34±0.00										
W-O		0.02±0.05										
W-P	0.23±0.01	0.34±0.02	35.58	7.45	17.59	24.22	0.318	0.137	0.181	0.057	-0.108	0.165
W-Q	-0.01±0	-0.01±0.00	90.62	160.10	2.72	93.32	-0.767	0.023	-0.790	0.385	-0.012	0.396
W-R	0.50±0.00	0.53±0.01	17.90	170.04	5.03	22.92	-0.159	0.045	-0.203	0.041	-0.008	0.049
W-S	0.51±0.00	0.70±0.02	5.71	145.03	10.09	11.48	-0.042	0.050	-0.092	0.042	0.107	-0.065
E-A	-0.02±0	-0.01±0.00	253.23	127.68	15.73	243.57	-1.391	-0.141	-1.250	2.533	-0.022	2.555
E-B	0.44±0.00	0.37±0.00	38.07	332.54	28.85	63.43	0.303	-0.111	0.415	-0.255	0.375	-0.630
E-C	0.27±0.02	0.34±0.00	55.39	116.87	26.99	34.24	-0.225	-0.201	-0.024	0.643	0.198	0.446
E-D	0.25±0.01	0.15±0.03	77.79	129.49	19.58	66.69	-0.444	-0.176	-0.268	0.754	0.002	0.751
E-E	0.20±0.06	0.33±0.00	58.52	303.83	17.00	73.42	0.292	-0.140	0.432	-0.650	0.090	-0.740
E-F	0.27±0.01	0.26±0.01	36.06	156.25	14.67	23.46	-0.297	-0.132	-0.165	0.179	-0.002	0.180
E-G	0.26±0.00	0.20±0.01	31.53	140.88	16.47	24.33	-0.220	-0.146	-0.074	0.248	-0.038	0.285
E-H	0.34±0.00	0.32±0.00	19.33	109.11	43.94	25.01	-0.057	-0.189	0.132	0.248	0.523	-0.275
E-I	0.07±0.01	0.11±0.02	58.58	98.35	46.67	24.24	-0.076	-0.220	0.144	0.774	0.530	0.244
E-J	0.26±0.02	0.27±0.00	32.78	201.71	13.78	20.53	-0.274	-0.124	-0.150	-0.150	-0.002	-0.149
E-K	0.14±0.02	0.06±0.00	255.50	128.33	32.87	220.19	-1.424	-0.179	-1.245	2.776	0.372	2.404
E-L	0.17±0.00											
E-M	0.12±0.00	0.14±0.01	24.89	69.78	11.73	35.73	0.077	0.013	0.064	0.265	-0.132	0.397
E-N	0.10±0.01	0.06±0.01	4.67	197.53	14.29	11.81	-0.040	-0.050	0.010	-0.016	-0.153	0.136

E-O	0.01±0.00	0.11±0.01	17.11	51.66	13.29	23.10	0.095	0.083	0.013	0.150	-0.107	0.256
E-P	0.08±0.01	0.03±0.01	22.46	42.86	16.79	38.54	0.148	-0.065	0.213	0.178	-0.175	0.353
E-Q	-0.04±0	-0.04±0.01	50.25	210.90	15.35	36.44	-0.388	-0.083	-0.305	-0.302	-0.144	-0.158
E-R	0.55±0.00	0.57±0.00	4.06	295.75	3.44	4.72	0.016	-0.024	0.040	-0.039	-0.022	-0.016
E-S	0.48±0.01	0.38±0.00	12.30	215.23	13.60	11.40	-0.090	-0.006	-0.085	-0.077	-0.147	0.070
E-T	-0.07±0	-0.05±0.00	32.19	359.15	9.81	23.15	0.290	0.083	0.207	-0.005	-0.037	0.031
E-U	0.16±0.01	0.19±0.01	6.53	297.66	4.70	2.46	0.027	0.008	0.019	-0.062	-0.049	-0.012
E-V	-0.07±0	-0.09±0.00	15.86	297.62	6.87	9.44	0.066	0.013	0.054	-0.151	-0.072	-0.079
E-W	0.06±0.01	0.10±0.00	5.60	214.18	12.23	10.42	-0.042	0.005	-0.046	-0.034	-0.133	0.099
E-X	0.05±0.02	0.17±0.01	5.84	228.87	12.38	7.62	-0.035	-0.028	-0.007	-0.050	-0.135	0.086
E-Y	0.14±0.00											
E-Z		0.26±0.00										
B-A	0.28±0.01	0.25±0.03	185.58	116.33	16.23	197.24	-0.739	-0.035	-0.704	2.555	-0.246	2.801
B-B	0.11±0.03	0.17±0.02	116.64	115.83	31.75	84.71	-0.456	-0.157	-0.299	1.501	0.382	1.119
B-C	0.32±0.03	0.39±0.00	30.72	104.53	29.20	59.88	-0.069	0.038	-0.107	0.456	-0.443	0.899
B-D	0.32±0.01	0.32±0.00	149.28	116.92	81.57	66.95	-0.606	-0.303	-0.303	1.915	1.076	0.839
B-E	0.48±0.02	0.48±0.02	44.51	283.27	38.74	5.87	0.092	0.086	0.006	-0.655	-0.567	-0.088
B-F	0.16±0.00											

Supplementary Table 5. Summary of previous studies quantifying past tree species range shift. Only studies reporting distance or degree shifts are included. 1-degree latitude = 111 km was assumed to convert degree shifts to distance shifts. Studies comparing adults and offsprings are not included due to difficulty in quantifying year gap.

Location	Dimension	Time	Margin	Life stage	Number of species	Mean distance shift (km·decade^{-1})	Minimum distance shift (km·decade^{-1})	Maximum distance shift (km·decade^{-1})	Reference
Quebec	Latitude	1970-1977 vs. 1992-2002	Median	Saplings (1.1 to 3.0 cm DBH)	11	5.58	0.04	19.01	(Boisvert-Marsh et al., 2014)
				Adults (DBH ≥ 9.1 cm)	11	1.61	0.08	4.98	
			Northern limit	Saplings (1.1 to 3.0 cm DBH)	11	7.18	1.78	16.44	
				Adults (DBH ≥ 9.1 cm)	11	3.04	0.66	7.70	
Eastern US	Latitude/Longitude	1980-1995 vs. 2013-2015	Mean	All	86	25.72	2.10	100.20	(Fei et al., 2017)
Northern Spain	Latitude	1971 vs. 2009-2010	Mean	All	2	0.44	0.38	0.50	(Hernández et al., 2014)
Quebec	Latitude	1970-1978 vs. 2000-2012	Northern limit	Adults (DBH ≥ 9 cm)	16	2.92	0.03	12.06	(Sittaro et al., 2017)
				Saplings (1-9 cm DBH)	16	4.64	0.22	11.51	

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