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Global Warming Drives Expansion of Endangered *Spruce* Forest on the Tibetan Plateau

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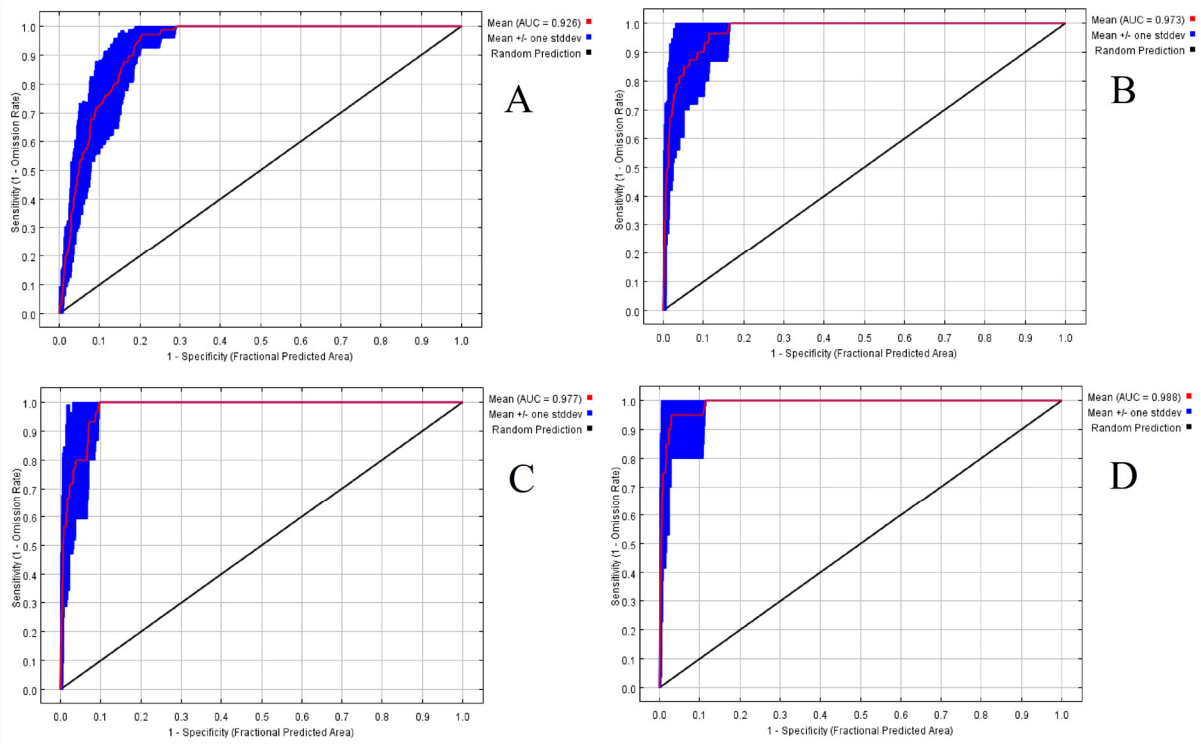


Figure S1. Average AUC training values for four endangered spruce species, A for *P. balfouriana*, B for *P. linzhiensis*, C for *P. complanata*, D for *P. aurantiaca*.

Table S1. Environment variables.

Category	Variable	Description	Unit	Variable	Description	Unit
Climate	Bio1	Annual mean temperature	℃	Bio11	Mean temperature of coldest quarter	℃
	Bio2	Mean diurnal range	℃	Bio12	Annual precipitation	mm
	Bio3	Isothermality	%	Bio13	Precipitation of wettest month	mm
	Bio4	Temperature seasonality	\	Bio14	Precipitation of driest month	mm
	Bio5	Max temperature of warmest month	℃	Bio15	Precipitation seasonality	%
	Bio6	Min temperature of coldest month	℃	Bio16	Precipitation of wettest quarter	mm
	Bio7	Temperature annual range	℃	Bio17	Precipitation of driest quarter	mm
	Bio8	Mean temperature of wettest quarter	℃	Bio18	Precipitation of warmest quarter	mm
	Bio9	Mean temperature of driest quarter	℃	Bio19	Precipitation of coldest quarter	mm
	Bio10	Mean temperature of warmest quarter	℃			
Topography	Ele	Elevation	m	Slo	Slope	°
	Asp	Aspect	°			
Soil	T_Gravel	Topsoil Gravel Content	%	T_Ph_H2o	Topsoil pH (H2O)	-log(H+)
	T_Sand	Topsoil Sand Fraction	%	T_Esp	Topsoil Sodicity (ESP)	%
	T_Silt	Topsoil silt fraction	%	S_Gravel	Subsoil Gravel Content	%
	T_Clay	Topsoil Clay Fraction	%	S_Clay	Subsoil Clay Fraction	%
	T_Ref	Topsoil Reference Bulk Density	kg/dm^3	S_Ref	Subsoil Reference Bulk Density	kg/dm^3

Table S2. Criteria for the classification of endangered spruce suitable areas.

Species	Suitable Level	Current	2041-2060			2061-2080			2081-2100		
			SSP126	SSP370	SSP585	SSP126	SSP370	SSP585	SSP126	SSP370	SSP585
P.balfouriana	Highly Suitable	0.496	0.555	0.555	0.554	0.523	0.578	0.570	0.572	0.569	0.620
	Moderately Suitable	0.284	0.323	0.326	0.325	0.299	0.343	0.338	0.339	0.334	0.382
	Minimally Suitable	0.093	0.107	0.111	0.109	0.097	0.114	0.110	0.114	0.114	0.134
P.linzhiensis	Highly Suitable	0.493	0.553	0.553	0.537	0.529	0.559	0.552	0.535	0.554	0.530
	Moderately Suitable	0.255	0.302	0.303	0.287	0.285	0.309	0.305	0.286	0.305	0.267
	Minimally Suitable	0.075	0.092	0.096	0.088	0.089	0.097	0.096	0.088	0.098	0.078
P.complanata	Highly Suitable	0.474	0.490	0.529	0.507	0.465	0.450	0.458	0.454	0.492	0.496
	Moderately Suitable	0.248	0.250	0.268	0.257	0.236	0.212	0.220	0.214	0.240	0.246
	Minimally Suitable	0.076	0.074	0.078	0.071	0.068	0.057	0.061	0.057	0.069	0.073
P.aurantiaca	Highly Suitable	0.472	0.613	0.549	0.632	0.577	0.591	0.635	0.668	0.650	0.704
	Moderately Suitable	0.231	0.330	0.282	0.347	0.306	0.332	0.362	0.378	0.364	0.400
	Minimally Suitable	0.066	0.100	0.084	0.108	0.092	0.103	0.115	0.120	0.112	0.128

Table S3. Area ($\times 10^4 km^2$) and proportion (%) of current suitable habitats for *P.balfouriana*, *P.linzhiensis*, *P.brachytyla* and *P.aurantiaca*.

Suitable Level	*P.balfouriana*		*P.linzhiensis*		*P.brachytyla*		*P.aurantiaca*	
	Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion
Highly Suitable	15.82	6.15	4.60	1.79	4.06	1.58	2.11	0.82
Moderately Suitable	21.87	8.50	7.82	3.04	6.25	2.43	4.32	1.68
Minimally Suitable	22.38	8.70	14.59	5.67	10.57	4.11	9.85	3.83
Suitable	60.07	23.35	27.01	10.50	20.88	8.12	16.28	6.33
Not Suitable	197.18	76.65	230.24	89.50	236.37	91.88	240.97	93.67

Table S4. Contribution of Environmental Variables.

Category	Variable	Description	Unit	Contribution(%)			
				P.balfouriana	*P.linzhiensis*	*P.complanata*	*P.aurantiaca*
Climate	Bio2	Mean diurnal range	℃	1.7		0.4	1.0
	Bio3	Isothermality	%	2.5			
	Bio4	Temperature seasonality	\	12.7	61.1	7.5	
	Bio5	Max temperature of warmest month	℃				2.7
	Bio7	Temperature annual range	℃				10
	Bio11	Mean temperature of coldest quarter	℃	5.0	11.7	14.3	10.6
	Bio12	Annual precipitation	mm	63.0	6.5	32.7	37.6
	Bio14	Precipitation of driest month	mm			12.3	
	Bio15	Precipitation seasonality	%			1.6	
	Bio17	Precipitation of driest quarter	mm				2.5
	Bio19	Precipitation of coldest quarter	mm		2.9		
Topography	Ele	Elevation	m				5.6
	Asp	Aspect	°		1.9	0.7	3
	Slo	Slope	°	1.8			8
Soil	T_Esp	Topsoil Sodicity (ESP)	%	11.3	5.3		17
	S_Gravel	Subsoil Gravel Content	%	2.0			
	S_Clay	Subsoil Clay Fraction	%		10.6	25.6	
	T_Gravel	Topsoil Gravel Content	%			4.1	2.0
	T_Silt	Topsoil silt fraction	%			0.6	

Table S5. Area (×10⁴ km²) and proportion (%) of suitable habitats under different future climate scenarios.

Species	Climate	Year	Highly Suitable		Moderately Suitable		Minimally Suitable		Suitable	
			Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion
P.balfouriana	SSP126	2041-2060	21.56	8.38	26.67	10.37	28.63	11.13	76.86	29.88
		2061-2080	18.75	7.29	24.37	9.47	25.08	9.75	68.20	26.51
		2081-2100	23.90	9.29	27.86	10.83	28.63	11.13	80.39	31.25
	SSP370	2041-2060	22.69	8.82	25.70	9.99	27.40	10.65	75.79	29.46
		2061-2080	24.03	9.34	25.60	9.95	25.98	10.10	75.61	29.39
		2081-2100	27.24	10.59	31.36	12.19	34.29	13.33	92.89	36.11
	SSP585	2041-2060	20.87	8.11	27.83	10.82	30.17	11.73	78.87	30.66
		2061-2080	28.27	10.99	26.39	10.26	29.02	11.28	83.68	32.53
		2081-2100	34.55	13.43	35.42	13.77	32.57	12.66	102.54	39.86
P.linzhiensis	SSP126	2041-2060	9.65	3.75	12.76	4.96	18.65	7.25	41.06	15.96
		2061-2080	7.30	2.84	10.65	4.14	15.51	6.03	33.47	13.01
		2081-2100	9.16	3.56	12.84	4.99	19.65	7.64	41.65	16.19
	SSP370	2041-2060	12.19	4.74	14.71	5.72	19.99	7.77	46.89	18.23
		2061-2080	11.70	4.55	14.77	5.74	18.41	7.16	44.89	17.45
		2081-2100	16.31	6.34	18.19	7.07	25.23	9.81	59.73	23.22
	SSP585	2041-2060	7.90	3.07	11.56	4.49	17.44	6.78	36.90	14.35
		2061-2080	11.22	4.36	14.22	5.53	19.47	7.57	44.91	17.46
		2081-2100	8.36	3.25	11.22	4.36	25.67	9.98	45.25	17.59
P.complanata	SSP126	2041-2060	5.32	2.07	9.62	3.74	16.41	6.38	31.35	12.19
		2061-2080	4.50	1.75	8.62	3.35	14.07	5.47	27.19	10.57
		2081-2100	5.27	2.05	12.05	4.68	23.38	9.09	40.70	15.82
	SSP370	2041-2060	5.07	1.97	10.37	4.03	18.08	7.03	33.52	13.03
		2061-2080	4.48	1.74	11.96	4.65	24.13	9.38	40.57	15.77
		2081-2100	5.22	2.03	12.48	4.85	31.41	12.21	49.11	19.09
	SSP585	2041-2060	5.71	2.22	10.91	4.24	20.96	8.15	37.58	14.61
		2061-2080	4.91	1.91	11.94	4.64	24.59	9.56	41.44	16.11
		2081-2100	5.76	2.24	12.77	4.97	33.85	13.16	52.40	20.37
P.aurantiaca	SSP126	2041-2060	7.64	2.97	10.29	4.00	15.56	6.05	33.49	13.02
		2061-2080	5.76	2.24	8.72	3.39	14.92	5.80	29.40	11.43
		2081-2100	11.52	4.48	12.22	4.75	16.49	6.41	40.23	15.64
	SSP370	2041-2060	5.76	2.24	9.67	3.76	16.28	6.33	31.71	12.33
		2061-2080	9.85	3.83	13.61	5.29	16.82	6.54	40.28	15.66
		2081-2100	13.94	5.42	13.84	5.38	19.01	7.39	46.79	18.19
	SSP585	2041-2060	9.67	3.76	12.19	4.74	16.85	6.55	38.71	15.05
		2061-2080	12.99	5.05	14.33	5.57	16.95	6.59	44.27	17.21
		2081-2100	26.57	10.33	17.93	6.97	23.56	9.16	68.07	26.46

Table S6. Area (×10^4 km^2) and proportion (%) of endangered spruce suitable habitat within the suitable growth range of the key variable under future climate scenarios.

Climate	Year	*P.balfouriana*		*P.linzhiensis*		*P.complanata*		*P.aurantiaca*	
		Area	Proportion	Area	Proportion	Area	Proportion	Area	Proportion
SSP126	2041-2060	67.78	88.19	35.08	85.45	30.36	96.84	27.75	82.86
	2061-2080	59.43	87.14	27.19	81.23	26.90	98.95	23.52	80.00
	2081-2100	75.16	93.50	36.82	88.41	37.61	92.41	34.31	85.29
SSP370	2041-2060	66.70	88.01	39.04	83.27	32.89	98.13	28.58	90.14
	2061-2080	68.82	91.02	40.72	90.72	40.14	98.94	34.88	86.60
	2081-2100	88.48	95.25	54.78	91.71	48.60	98.97	39.91	85.29
SSP585	2041-2060	74.09	93.94	32.09	86.96	36.48	97.07	34.79	89.88
	2061-2080	76.31	91.19	40.74	90.71	39.66	95.70	40.60	91.72
	2081-2100	99.82	97.35	43.34	95.78	48.38	92.33	61.80	90.79

Table S7. Changes of distribution area (×10⁴ km²) and proportion (%) of *P.balfouriana*, *P.linzhiensis*, *P.complanata* and *P.aurantiaca* under different future climate scenarios.

Species	Climate	Year	Lost		Remain		Gain		Change Trend
			Area	Proportion	Area	Proportion	Area	Proportion	
P.balfouriana	SSP126	2041-2060	0.80	0.31	238.98	92.90	17.47	6.79	Expansion
		2061-2080	0.36	0.14	248.43	96.57	8.46	3.29	Expansion
		2081-2100	0.75	0.29	235.43	91.52	21.07	8.19	Expansion
	SSP370	2041-2060	0.98	0.38	239.65	93.16	16.62	6.46	Expansion
		2061-2080	0.80	0.31	240.14	93.35	16.31	6.34	Expansion
		2081-2100	0.31	0.12	223.91	87.04	33.03	12.84	Expansion
	SSP585	2041-2060	1.23	0.48	235.95	91.72	20.07	7.80	Expansion
		2061-2080	0.69	0.27	232.22	90.27	24.34	9.46	Expansion
		2081-2100	2.19	0.85	210.53	81.84	44.53	17.31	Expansion
P.linzhiensis	SSP126	2041-2060	2.50	0.97	238.26	92.62	16.49	6.41	Expansion
		2061-2080	1.54	0.60	247.84	96.34	7.87	3.06	Expansion
		2081-2100	3.73	1.45	235.23	91.44	18.29	7.11	Expansion
	SSP370	2041-2060	1.42	0.55	234.61	91.20	21.22	8.25	Expansion
		2061-2080	1.80	0.70	235.87	91.69	19.58	7.61	Expansion
		2081-2100	3.60	1.40	217.40	84.51	36.25	14.09	Expansion
	SSP585	2041-2060	5.38	2.09	236.67	92.00	15.20	5.91	Expansion
		2061-2080	1.98	0.77	235.51	91.55	19.76	7.68	Expansion
		2081-2100	9.34	3.63	220.41	85.68	27.50	10.69	Expansion
P.complanata	SSP126	2041-2060	1.08	0.42	244.72	95.13	11.45	4.45	Expansion
		2061-2080	0.54	0.21	249.94	97.16	6.77	2.63	Expansion
		2081-2100	0.87	0.34	235.67	91.61	20.71	8.05	Expansion
	SSP370	2041-2060	0.51	0.20	243.57	94.68	13.17	5.12	Expansion

		2061-2080	1.49	0.58	234.46	91.14	21.30	8.28	Expansion
		2081-2100	2.44	0.95	224.12	87.12	30.69	11.93	Expansion
	SSP585	2041-2060	0.75	0.29	239.14	92.96	17.36	6.75	Expansion
		2061-2080	1.65	0.64	233.32	90.70	22.28	8.66	Expansion
		2081-2100	3.14	1.22	219.30	85.25	34.81	13.53	Expansion
P.aurantiaca	SSP126	2041-2060	0.82	0.32	238.42	92.68	18.01	7.00	Expansion
		2061-2080	0.41	0.16	243.33	94.59	13.51	5.25	Expansion
		2081-2100	1.11	0.43	231.14	89.85	25.00	9.72	Expansion
	SSP370	2041-2060	1.36	0.53	239.09	92.94	16.80	6.53	Expansion
		2061-2080	2.29	0.89	228.67	88.89	26.29	10.22	Expansion
		2081-2100	2.57	1.00	221.55	86.12	33.13	12.88	Expansion
	SSP585	2041-2060	11.58	0.45	232.50	90.38	23.59	9.17	Expansion
		2061-2080	2.42	0.94	224.37	87.22	30.46	11.84	Expansion
		2081-2100	2.75	1.07	199.91	77.71	54.59	21.22	Expansion