

**Felix Eigenbrod<sup>1</sup>, Patrick Gonzalez<sup>2</sup>, Jadunandan Dash<sup>3</sup>, and Ilse Steyl<sup>1</sup>**. 2015. Vulnerability of ecosystems to climate change moderated by habitat intactness. *Global Change Biology* 21: 275-286.

1. Centre for Biological Sciences, University of Southampton, Southampton SO17 1BJ, UK
2. Natural Resource Stewardship and Science, U.S. National Park Service, Washington, DC 20005-5905, USA
3. Geography and Environment, University of Southampton SO17 1BJ, Southampton, UK

### **Supporting Information**

**Table S1.** Habitat loss, fraction (%) of terrestrial vegetated area.

Scale	Intactness	Area	Very low	Low	Medium	High	Very high
<b>4.8 km</b>	<b>nlc</b>	<b>World</b>	<b>18</b>	<b>50</b>	<b>27</b>	<b>3</b>	<b>2</b>
		Africa	14	59	25	1	<0.5
		Asia	13	42	32	7	6
		Australia	31	47	19	2	<0.5
		Europe	3	40	54	3	<0.5
		North America	18	70	12	<0.5	0
		South America	34	35	30	1	<0.5
		<b>4.8 km</b>	<b>ltw</b>	<b>World</b>	<b>7</b>	<b>14</b>	<b>26</b>
Africa	2	5		22	9	63	
Asia	5	15		23	5	52	
Australia	12	25		39	8	16	
Europe	1	4		13	6	77	
North America	7	24		33	8	28	
South America	17	8		27	9	39	
<b>4.8 km</b>	<b>wpa</b>	<b>World</b>		<b>&lt;0.5</b>	<b>2</b>	<b>8</b>	<b>7</b>
		Africa	<0.5	1	7	5	86
		Asia	<0.5	1	5	7	87
		Australia	<0.5	1	9	9	80
		Europe	0	<0.5	5	13	81
		North America	1	2	8	9	80
		South America	1	4	15	2	78
		<b>48 km</b>	<b>nlc</b>	<b>World</b>	<b>19</b>	<b>43</b>	<b>34</b>
Africa	14			51	33	0	1
Asia	14			39	36	0	11
Australia	30			47	20	0	3
Europe	3			33	62	0	2
North America	19			53	27	0	<0.5
South America	34			32	33	0	1
<b>48 km</b>	<b>ltw</b>			<b>World</b>	<b>14</b>	<b>18</b>	<b>5</b>
		Africa	7	10	2	0	81
		Asia	11	20	5	0	64
		Australia	28	32	6	0	34
		Europe	2	9	2	0	88
		North America	13	27	11	0	48
		South America	27	10	4	0	59
		<b>48 km</b>	<b>wpa</b>	<b>World</b>	<b>1</b>	<b>2</b>	<b>1</b>
Africa	1			3	1	0	95
Asia	1			2	1	0	97
Australia	2			2	1	0	95
Europe	<0.5			1	<0.5	0	99
North America	2			3	2	0	94
South America	4			1	<0.5	0	94

**Table S2.** Vulnerability to biome shifts due to climate change (Gonzalez et al. 2010), fraction (%) of terrestrial area. These results exclude the GlobCover classes for bare areas, snow, and ice.

Area	Very low	Low	Medium	High	Very high
<b>World</b>	<b>1</b>	<b>23</b>	<b>63</b>	<b>12</b>	<b>1</b>
Africa	1	30	58	10	1
Asia	<0.5	18	65	15	1
Australia	<0.5	47	48	4	<0.5
Europe	0	8	81	11	<0.5
North America	<0.5	23	62	14	<0.5
South America	1	20	64	14	1

Gonzalez, P., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2010. Global patterns in the vulnerability of ecosystems to vegetation shifts due to climate change. *Global Ecology and Biogeography* 19: 755-768.

**Table S3.** Refugia and high vulnerability areas (% of biome area) by biome. Biomes are in order of predominant location from the Poles to the Equator.

Biome	4.8 km						48 km					
	nlc	nlc	ltw	ltw	wpa	wpa	nlc	nlc	ltw	ltw	wpa	wpa
	refugia	high vuln.	refugia	high vuln.	refugia	high vuln.	refugia	high vuln.	refugia	high vuln.	refugia	high vuln.
Ice	36	0	29	0	14	14	43	0	43	0	21	14
Tundra and Alpine	34	<0.5	22	5	3	69	36	<0.5	32	14	5	75
Boreal Conifer Forest	24	2	12	21	<0.5	72	22	2	18	38	1	83
Temperate Conifer Forest	16	1	1	58	<0.5	62	14	3	5	67	1	71
Temperate Broadleaf Forest	19	2	<0.5	62	<0.5	59	17	4	1	65	<0.5	66
Temperate Mixed Forest	6	2	<0.5	81	0	80	6	3	1	88	<0.5	91
Temperate Shrubland	22	3	1	38	<0.5	64	21	5	12	52	1	73
Temperate Grassland	15	1	<0.5	43	0	69	13	3	6	60	<0.5	75
Desert	49	3	20	15	2	52	48	4	42	21	3	60
Tropical Grassland	33	3	11	35	1	70	32	5	24	49	1	77
Tropical Woodland	14	11	3	55	1	79	14	12	7	67	1	85
Tropical Deciduous Broadleaf Forest	29	3	5	49	2	56	27	6	10	60	3	64
Tropical Evergreen Broadleaf Forest	46	1	17	34	2	51	47	2	25	42	4	60
Global analysis area	29	2	10	37	1	64	28	4	17	48	2	73

**Table S4.** Refugia and high vulnerability areas (million km<sup>2</sup>) by biome. Biomes are in order of predominant location from the Poles to the Equator.

Biome	4.8 km						48 km						
	nlc	nlc	ltw	ltw	wpa	wpa	nlc	nlc	ltw	ltw	wpa	wpa	
	total	refugia	high vuln.	refugia	high vuln.	refugia	high vuln.	refugia	high vuln.	refugia	high vuln.	refugia	high vuln.
Ice	<0.1	<0.1	0	<0.1	0	<0.1	<0.1	<0.1	0	<0.1	0	<0.1	<0.1
Tundra and Alpine	10.0	3.3	<0.1	2.3	0.5	0.3	6.9	3.5	<0.1	3.2	1.3	0.5	7.6
Boreal Conifer Forest	19.4	4.6	0.3	2.4	4.0	<0.1	13.9	4.2	0.4	3.5	7.3	0.2	16.1
Temperate Conifer Forest	4.6	0.7	<0.1	<0.1	2.7	<0.1	2.9	0.6	0.2	0.2	3.1	<0.1	3.3
Temperate Broadleaf Forest	6.0	1.1	0.1	<0.1	3.7	<0.1	3.5	1.0	0.3	0.1	3.9	<0.1	3.9
Temperate Mixed Forest	5.0	0.3	0.1	<0.1	4.1	0	4.0	0.3	0.1	<0.1	4.4	<0.1	4.6
Temperate Shrubland	6.0	1.3	0.2	<0.1	2.3	<0.1	3.9	1.3	0.3	0.7	3.1	<0.1	4.3
Temperate Grassland	4.4	0.7	0.1	<0.1	1.9	0	3.1	0.6	0.1	0.3	2.6	<0.1	3.3
Desert	2.3	1.1	0.1	0.5	0.4	<0.1	1.2	1.1	0.1	1.0	0.5	0.1	1.4
Tropical Grassland	12.6	4.2	0.4	1.4	4.5	0.1	8.9	4.1	0.7	3.0	6.2	0.2	9.7
Tropical Woodland	6.2	0.9	0.7	0.2	3.4	<0.1	4.9	0.9	0.8	0.4	4.2	0.1	5.3
Tropical Deciduous Broadleaf Forest	12.5	3.6	0.4	0.7	6.2	0.2	7.0	3.4	0.7	1.3	7.4	0.4	8.1
Tropical Evergreen Broadleaf Forest	19.6	9.1	0.2	3.3	6.6	0.4	10.0	9.2	0.4	5.0	8.3	0.7	11.8
Global analysis area	108.8	31.0	2.6	10.9	40.1	1.1	70.2	30.2	4.1	18.8	52.3	2.2	79.5

**Table S5.** Analysis of the sensitivity of the vulnerability to biome shifts due to climate change, as mediated by habitat intactness, to intactness thresholds, for North America; fraction (%) of terrestrial vegetated area.

Scale (km)	Intactness	Threshold (%)	Very low	Low	Medium	High	Very high
4.8	ltw	25	0	13	65	22	<0.5
4.8	ltw	50	0	11	65	23	<0.5
4.8	ltw	75	0	11	64	25	<0.5
4.8	wpa	25	0	2	37	61	<0.5
4.8	wpa	50	0	1	35	64	<0.5
4.8	wpa	75	0	1	33	65	<0.5
48	ltw	25	<0.5	21	50	29	<0.5
48	ltw	50	<0.5	18	45	37	<0.5
48	ltw	75	0	13	41	46	<0.5
48	wpa	25	0	4	27	69	<0.5
48	wpa	50	0	3	25	72	<0.5
48	wpa	75	0	2	24	73	<0.5

**Table S6.** Vulnerability to biome shifts due to climate change, as mediated by habitat intactness, of the U.S. National Park System; fraction (%) of area.

Scale	Intactness	Very low	Low	Medium	High	Very high
<b>Vulnerability to biome shifts due to climate change</b>						
All biomes		<0.5	32	51	16	<0.5
Excluding bare areas, snow, and ice		<0.5	30	52	17	<0.5
<b>Habitat fragmentation</b>						
4.8 km	nlc	16	75	9	0	0
4.8 km	ltw	<0.5	43	45	5	7
4.8 km	wpa	1	19	49	14	16
48 km	nlc	16	53	31	0	0
48 km	ltw	10	37	26	0	27
48 km	wpa	7	31	18	0	45
<b>Vulnerability to biome shifts due to climate change, mediated by habitat intactness</b>						
4.8 km	nlc	0	37	63	0	0
4.8 km	ltw	0	12	84	4	<0.5
4.8 km	wpa	0	7	81	12	<0.5
48 km	nlc	0	31	69	0	0
48 km	ltw	0	20	62	19	<0.5
48 km	wpa	0	16	53	31	<0.5

**Table S7.** Refugia and high vulnerability areas (% of biome area) of the U.S. National Park System, by biome. Biomes are in order of predominant location from the North Pole to the Equator.

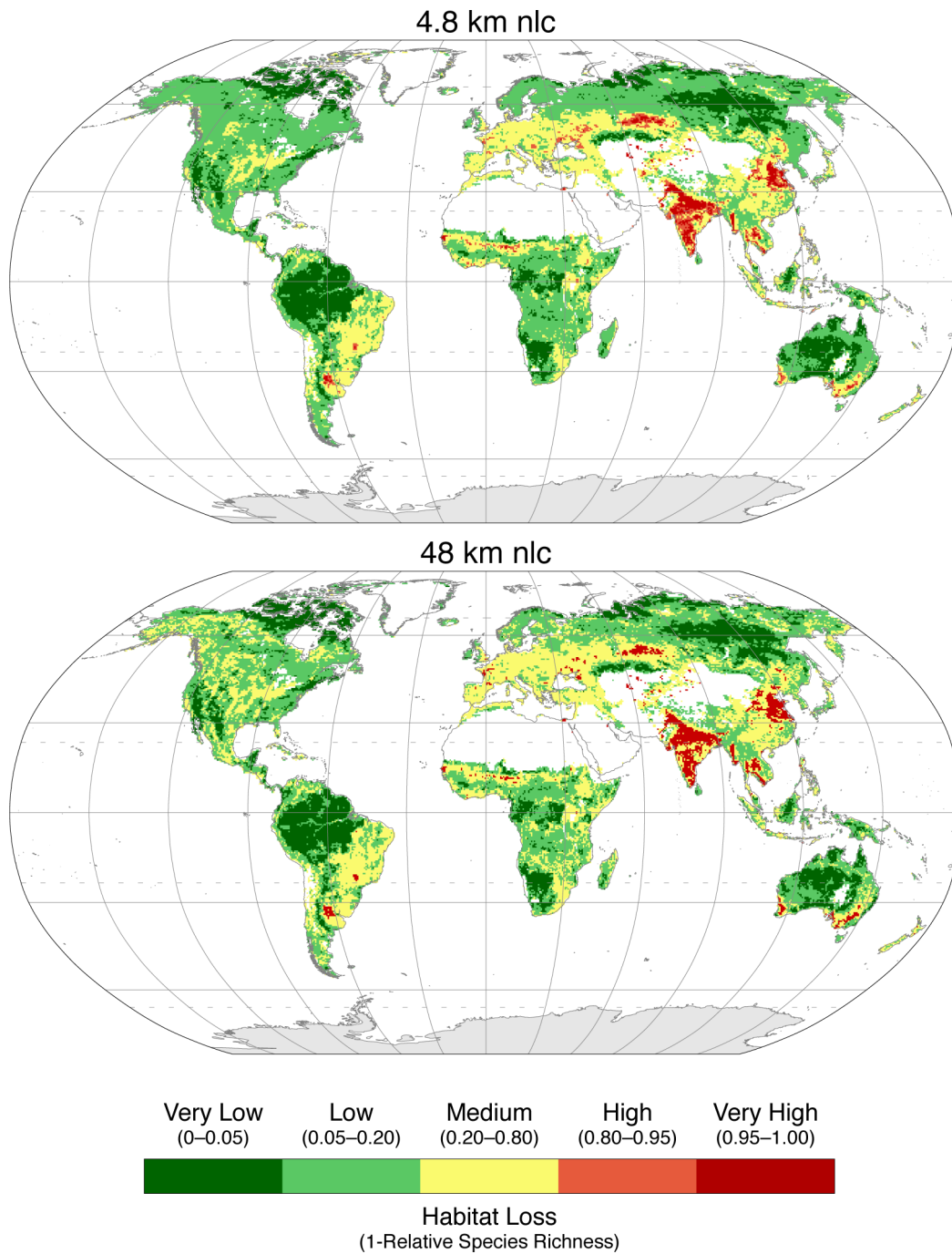
Biome	fraction of total	4.8 km						48 km					
		nlc refugia	nlc high vuln.	ltw refugia	ltw high vuln.	wpa refugia	wpa high vuln.	nlc refugia	nlc high vuln.	ltw refugia	ltw high vuln.	wpa refugia	wpa high vuln.
Ice	0	-	-	-	-	-	-	-	-	-	-	-	-
Tundra and Alpine	39	20	0	17	0	9	14	22	0	22	3	19	23
Boreal Conifer Forest	19	36	0	25	1	4	10	7	0	6	17	5	23
Temperate Conifer Forest	6	58	0	3	9	14	11	58	0	16	42	30	35
Temperate Broadleaf Forest	6	58	0	0	12	0	12	57	0	0	42	0	24
Temperate Mixed Forest	2	11	0	0	41	0	43	11	0	0	63	0	49
Temperate Shrubland	19	46	0	2	5	7	8	46	0	31	27	17	50
Temperate Grassland	3	49	0	<0.5	4	0	16	46	0	19	41	23	47
Desert	2	100	0	0	<0.5	27	<0.5	100	0	93	7	56	28
Tropical Grassland	2	83	0	6	13	0	14	83	0	31	16	40	19
Tropical Woodland	<0.5	0	0	0	100	0	100	0	0	0	100	0	100
Tropical Deciduous Broadleaf Forest	1	0	0	0	0	0	0	0	0	0	4	0	100
Tropical Evergreen Broadleaf Forest	1	78	0	0	22	0	10	78	0	21	79	78	22
U.S. National Park System	100	37	0	12	4	7	12	31	0	20	19	16	31



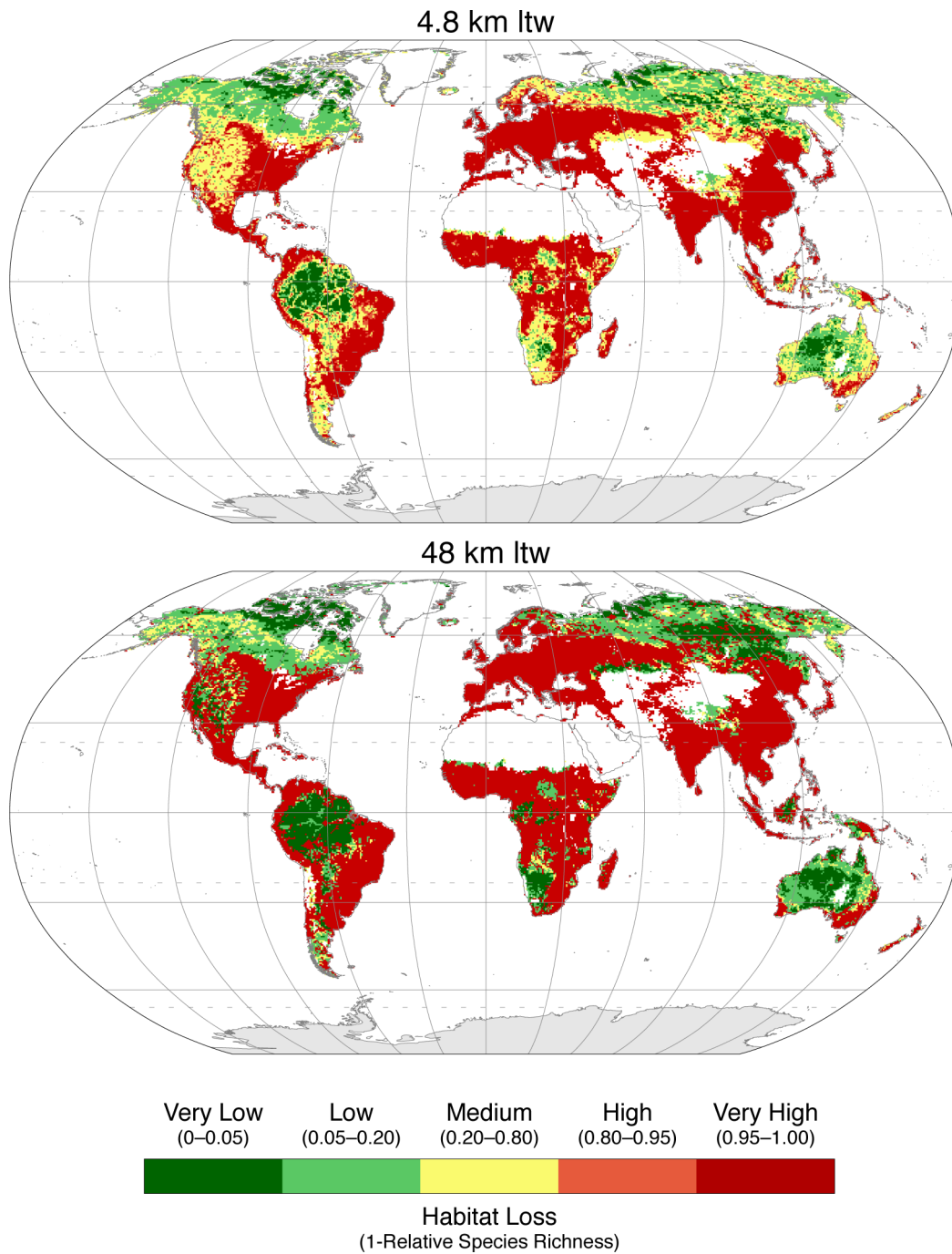
**Table S8.** Refugia and high vulnerability areas (thousand km<sup>2</sup>) of the U.S. National Park System, by biome. Biomes are in order of predominant location from the North Pole to the Equator. Total area is less than 340 000 km<sup>2</sup> due to coarse spatial resolution of data.

Biome	4.8 km							48 km					
	nlc		ltw		wpa		nlc		ltw		wpa		
	total	refugia	high vuln.	refugia	high vuln.	refugia	high vuln.	refugia	high vuln.	refugia	high vuln.	refugia	high vuln.
Ice	0	0	0	0	0	0	0	0	0	0	0	0	0
Tundra and Alpine	125	25	0	21	0	11	18	27	0	27	4	23	29
Boreal Conifer Forest	61	22	0	15	1	2	6	4	0	3	10	3	14
Temperate Conifer Forest	18	10	0	<0.5	2	3	2	10	0	3	8	5	6
Temperate Broadleaf Forest	19	11	0	0	2	0	2	11	0	0	8	0	4
Temperate Mixed Forest	8	1	0	0	3	0	3	1	0	0	5	0	4
Temperate Shrubland	59	27	0	1	3	4	5	27	0	19	16	10	30
Temperate Grassland	11	5	0	<0.5	<0.5	0	2	5	0	2	4	2	5
Desert	6	6	0	0	<0.5	2	<0.5	6	0	6	<0.5	3	2
Tropical Grassland	6	5	0	<0.5	1	0	1	5	0	2	1	2	1
Tropical Woodland	<0.5	0	0	0	<0.5	0	<0.5	0	0	0	<0.5	0	<0.5
Tropical Deciduous Broadleaf Forest	2	0	0	0	0	0	0	0	0	0	<0.5	0	2
Tropical Evergreen Broadleaf Forest	4	3	0	0	1	0	<0.5	3	0	1	3	3	1
U.S. National Park System	318	116	0	38	13	21	39	99	0	62	60	52	98

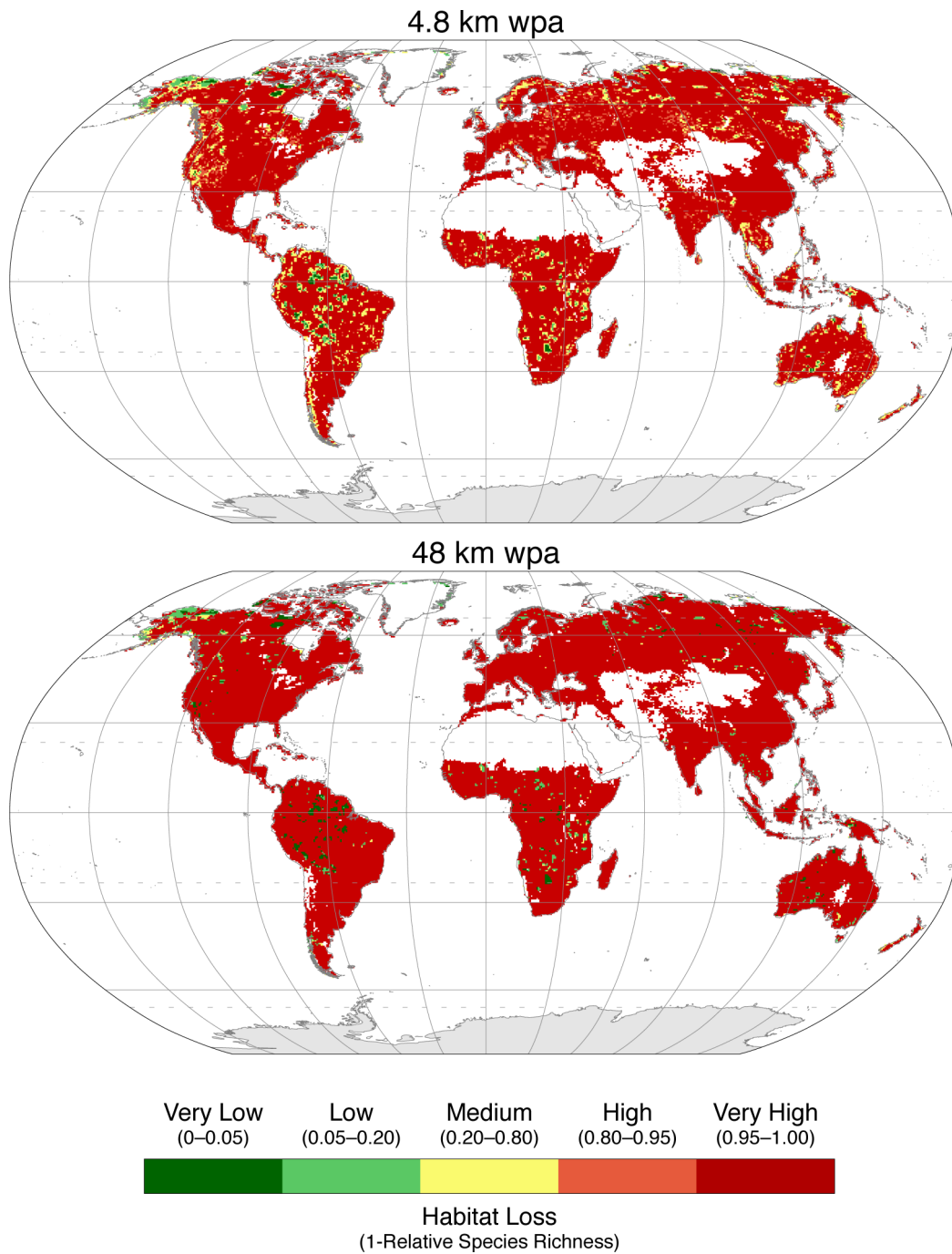
**Figure S1.** Habitat loss, with intact habitat defined as all natural vegetated GlobCover land classes.



**Figure S2.** Habitat loss, with intact habitat defined as all natural vegetated GlobCover land classes with  $\geq 50\%$  of the area in wilderness.



**Figure S3.** Habitat loss, with intact habitat defined as all natural vegetated GlobCover land classes with  $\geq 50\%$  of the area in protected areas.



**Figure S4.** Vulnerability to biome shifts across North America due to climate change, as mediated by habitat intactness, at the 48 x 48 km spatial scale with intact habitat defined as all natural vegetated GlobCover land classes with  $\geq 50\%$  of the area in wilderness (ltw). Bare areas, snow, and ice are not masked.

