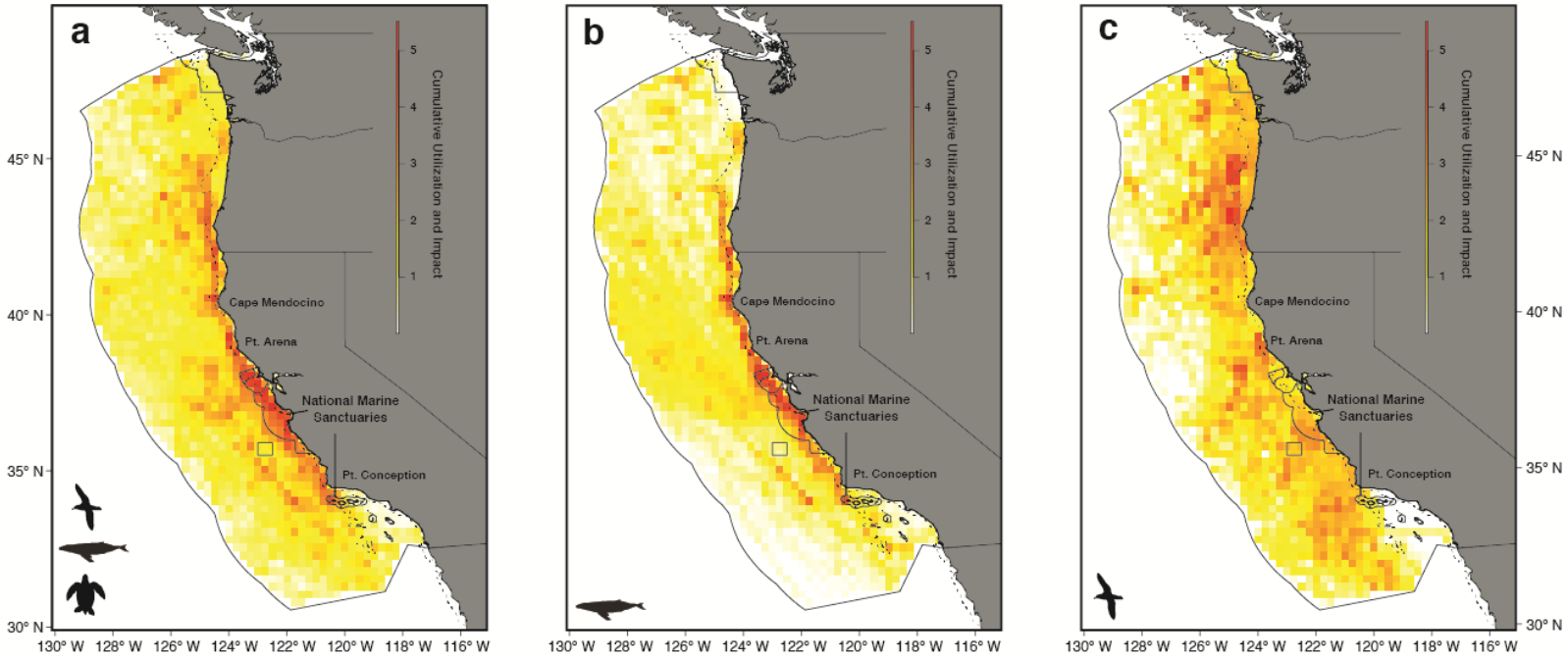
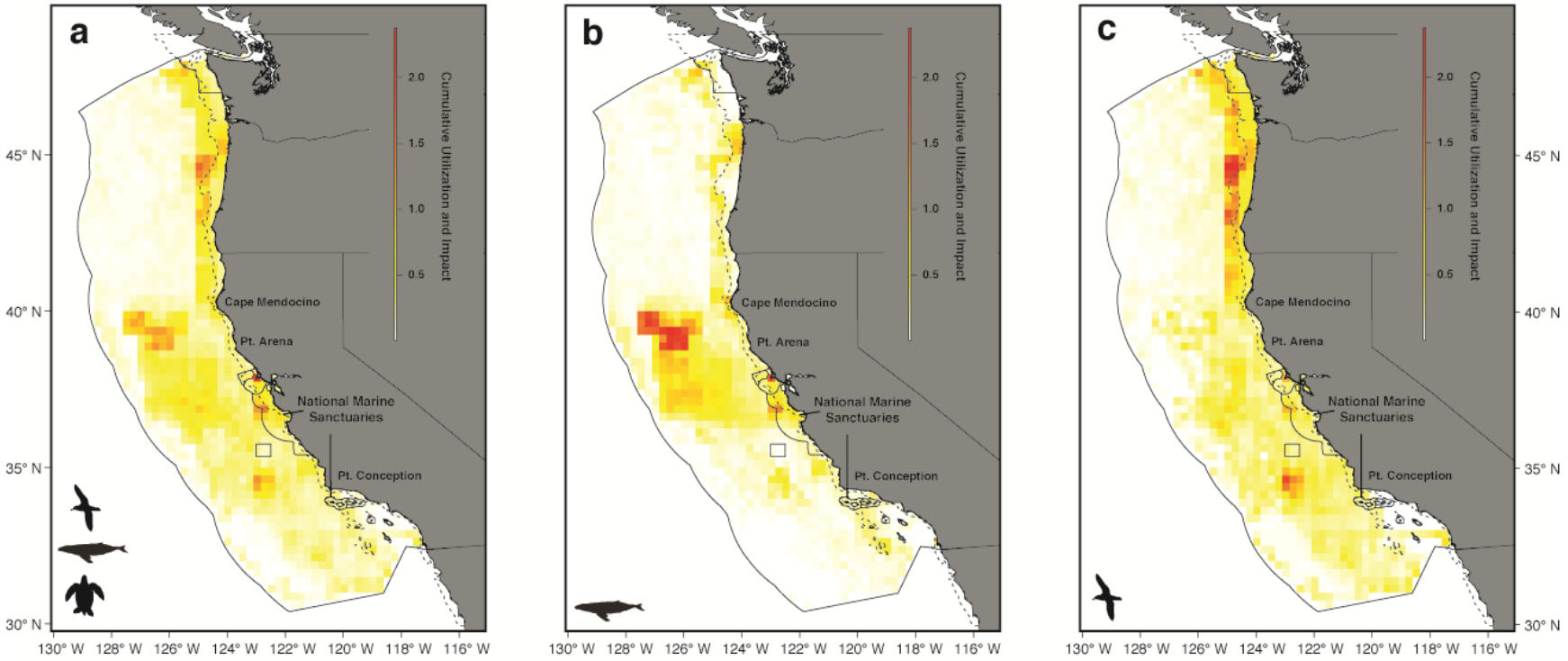
Supplementary Information

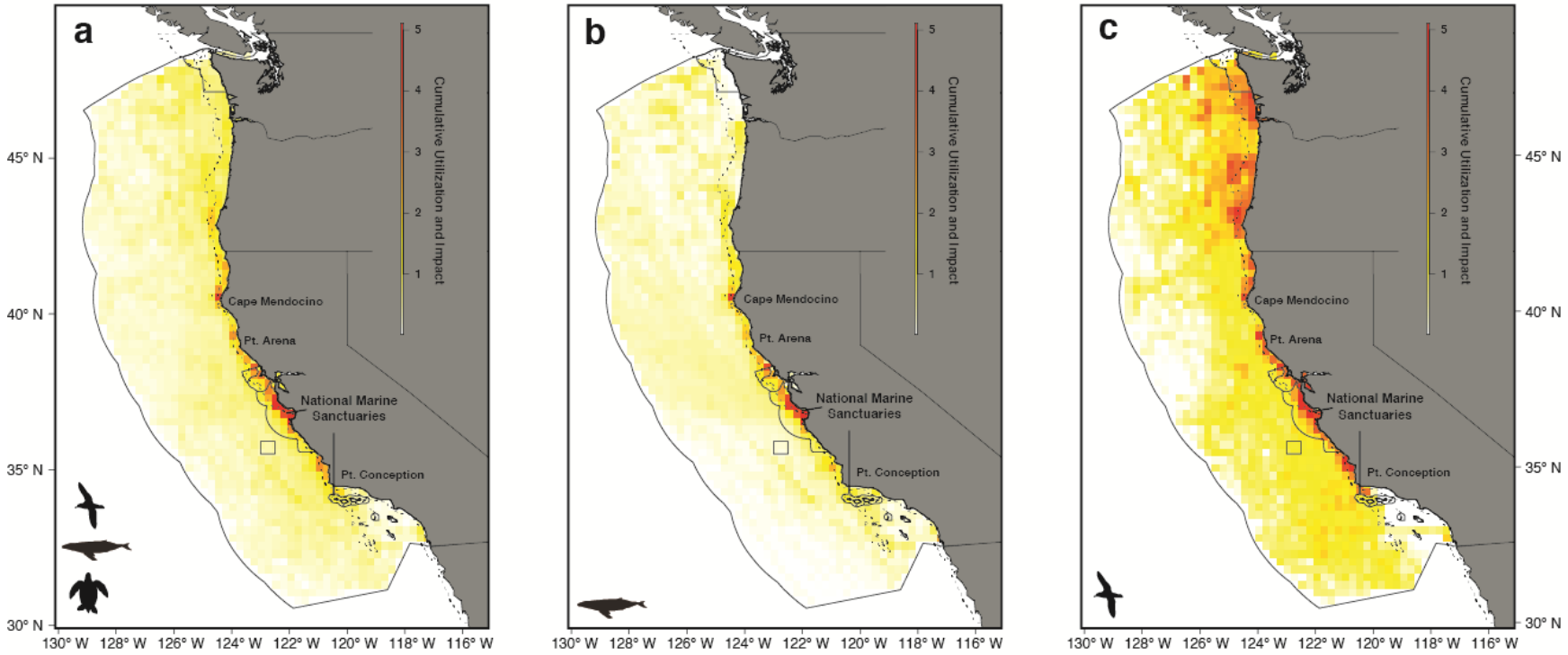
Cumulative human impacts on marine predators
S. M. Maxwell, et al. *Nature Communications.*



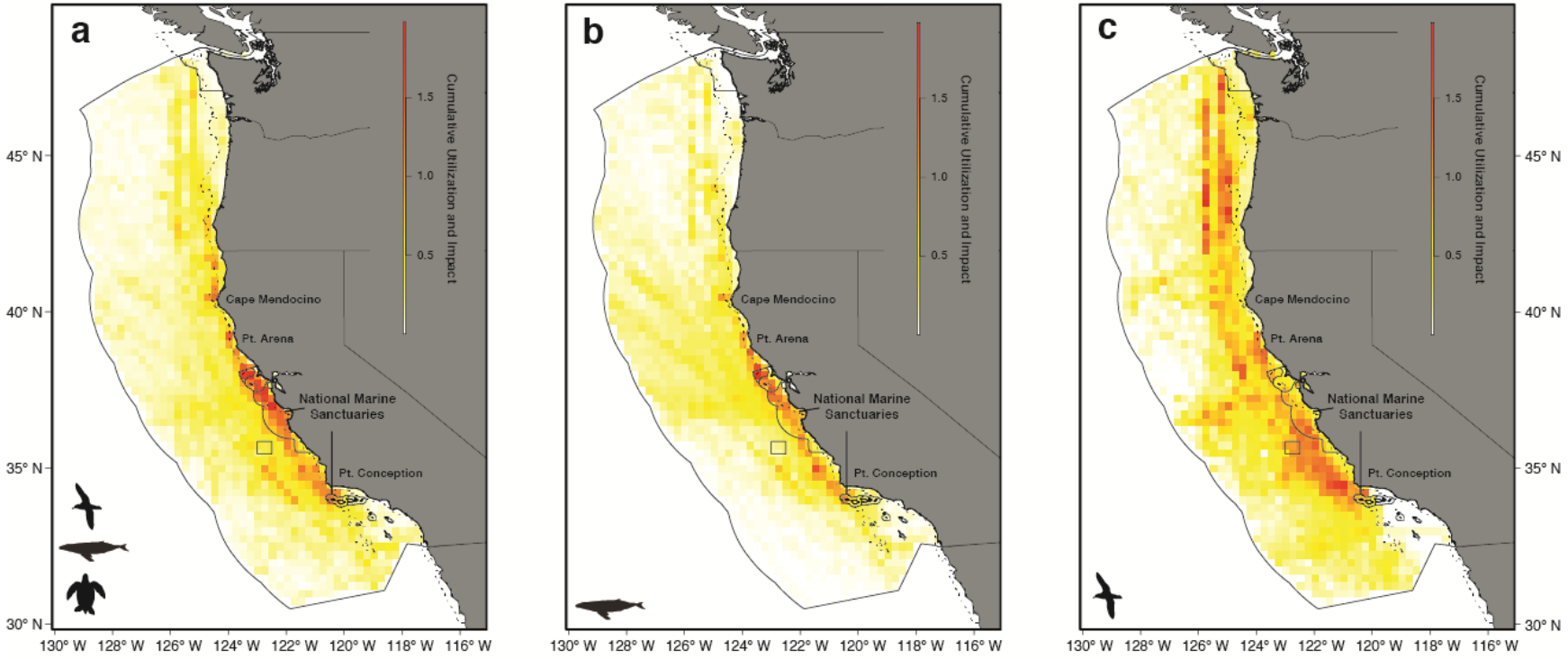
Supplementary Figure S1.Climate cumulative utilization and impact. Climate cumulative utilization and impact (CUI) for (a) all species combined, (b) marine mammals and (c) seabirds. Solid outer line represents US EEZ, solid inner lines represent National Marine Sanctuaries and dashed lines represent 200 m isobath.



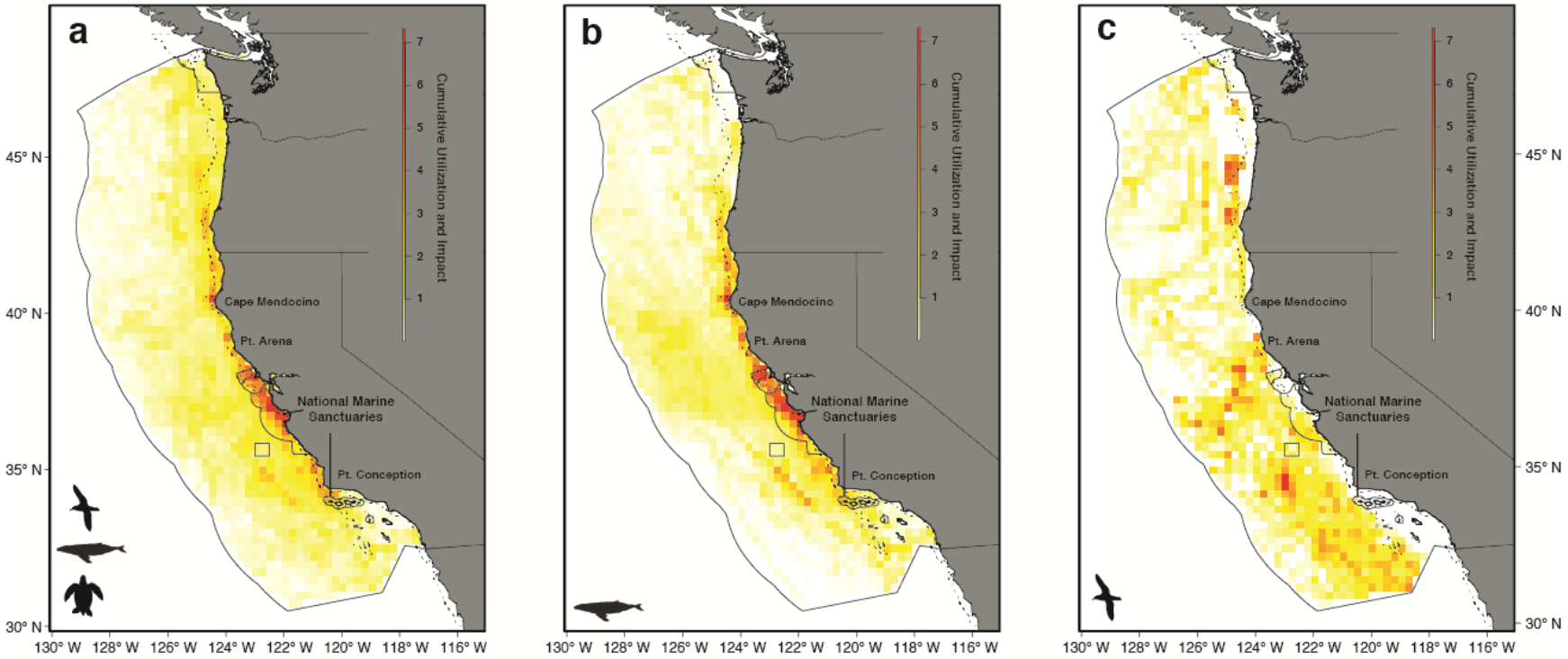
Supplementary Figure S2. Fishing cumulative utilization and impact. Fishing cumulative utilization and impact (CUI) for (a) all species combined, (b) marine mammals and (c) seabirds. Solid outer line represents US EEZ, solid inner lines represent National Marine Sanctuaries and dashed lines represent 200 m isobath.



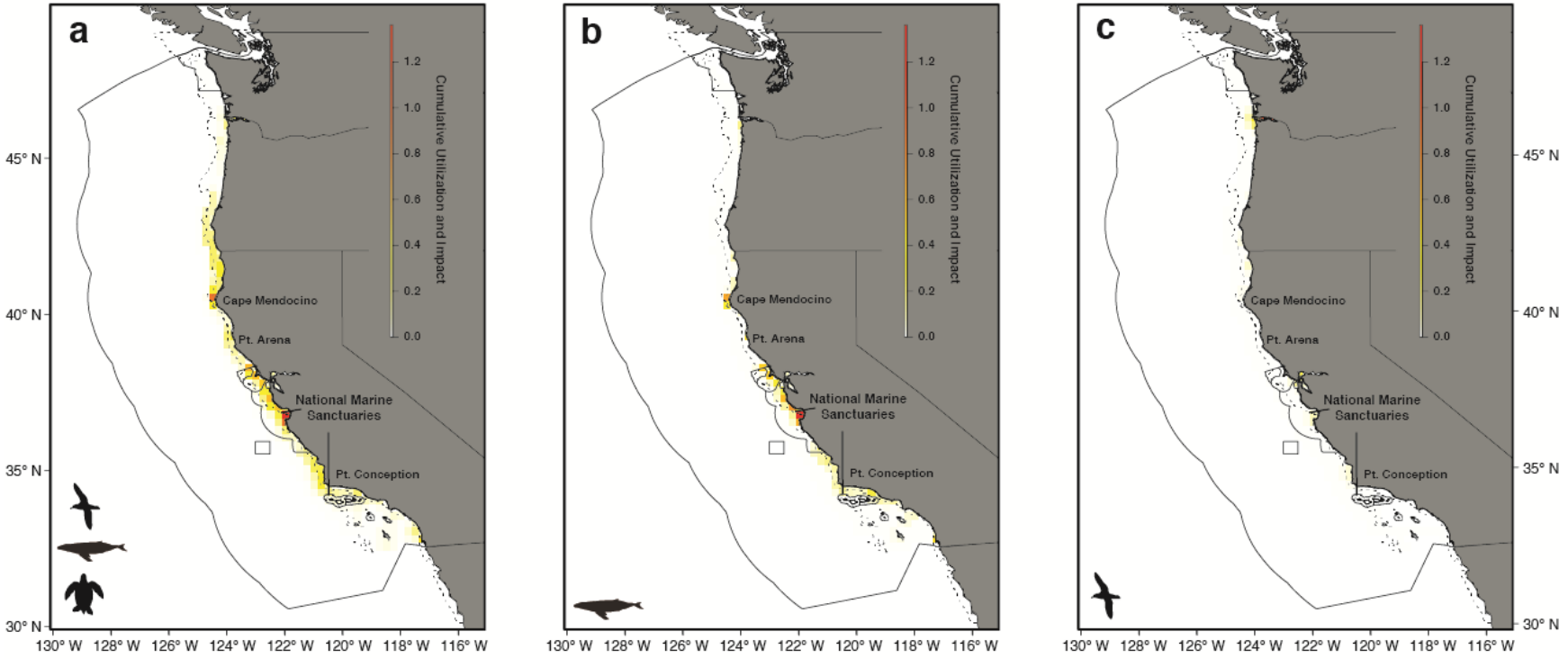
Supplementary Figure S3. Pollution cumulative utilization and impact. Pollution cumulative utilization and impact (CUI) for (a) all species combined, (b) marine mammals and (c) seabirds. Solid outer line represents US EEZ, solid inner lines represent National Marine Sanctuaries and dashed lines represent 200 m isobath.



Supplementary Figure S4. Shipping cumulative utilization and impact. Shipping cumulative utilization and impact (CUI) for (a) all species combined, (b) marine mammals and (c) seabirds. Solid outer line represents US EEZ, solid inner lines represent National Marine Sanctuaries and dashed lines represent 200 m isobath.



Supplementary Figure S5. Direct cumulative utilization and impact. Direct cumulative utilization and impact (CUI) for (a) all species combined, (b) marine mammals and (c) seabirds. Solid outer line represents US EEZ, solid inner lines represent National Marine Sanctuaries and dashed lines represent 200 m isobath.



Supplementary Figure S6. Coastal cumulative utilization and impact. Coastal cumulative utilization and impact (CUI) for (a) all species combined, (b) marine mammals and (c) seabirds. Solid outer line represents US EEZ, solid inner lines represent National Marine Sanctuaries and dashed lines represent 200 m isobath.

Supplementary Table S1. The influence of individual cumulative utilization and impact layers on the overall CUI for each species group.

		All Species				Marine Mammals				Seabirds				Sea Turtles			
			Per pixel fraction of total				Per pixel fraction of total				Per pixel fraction of total				Per pixel fraction of total		
Layer	Layer category	R^2	Average	SD	Max	R^2	Average	SD	Max	R^2	Average	SD	Max	R^2	Average	SD	Max
Ultraviolet radiation	Climate	0.8926	0.1938	0.0359	0.2744	0.8908	0.2045	0.0422	0.3528	0.9521	0.1832	0.0391	0.2667	0.8849	0.2408	0.0370	0.3168
Ocean acidification	Climate	0.8426	0.2861	0.0624	0.4886	0.9006	0.3068	0.0591	0.4905	0.9439	0.3092	0.0590	0.4882	0.8675	0.2325	0.0399	0.3323
Ocean pollution	Pollution	0.7886	0.0881	0.0418	0.5639	0.7605	0.0790	0.0337	0.2651	0.8027	0.0961	0.0409	0.3079	0.8953	0.0818	0.0180	0.1624
Shipping	Shipping	0.7358	0.0842	0.0449	0.2374	0.6684	0.0774	0.0391	0.2233	0.7253	0.0534	0.0292	0.1662	0.8780	0.1686	0.0286	0.2449
SST change	Climate	0.7318	0.1364	0.0593	0.3442	0.6550	0.1288	0.0649	0.3446	0.8156	0.1281	0.0641	0.3434	0.8462	0.1555	0.0458	0.2424
Ocean deposition	Pollution	0.4221	0.0949	0.0470	0.2470	0.5050	0.1006	0.0489	0.2421	0.7802	0.0994	0.0470	0.2470	0.0000	0.0000	0.0000	0.0000
Invasive species	Shipping	0.4009	0.0023	0.0084	0.1408	0.1416	0.0004	0.0031	0.0594	0.0309	0.0004	0.0025	0.0346	0.3900	0.0036	0.0125	0.0670
Organic pollution	Pollution	0.4000	0.0026	0.0100	0.1333	0.0379	0.0001	0.0007	0.0153	0.0036	0.0004	0.0061	0.1333	0.4281	0.0052	0.0180	0.1025
Nutrient deposition	Pollution	0.3776	0.0022	0.0092	0.1621	0.1164	0.0001	0.0009	0.0303	0.0062	0.0006	0.0081	0.1621	0.3999	0.0024	0.0078	0.0504
Coastal waste	Pollution	0.2717	0.0119	0.0491	0.6309	0.3116	0.0112	0.043	0.3655	0.0615	0.0104	0.0453	0.3818	0.3602	0.0068	0.0265	0.1817
Inorganic pollution	Pollution	0.2577	0.0015	0.0077	0.1621	0.0979	0.0002	0.0008	0.0102	0.0040	0.0005	0.0070	0.1621	0.3579	0.0027	0.0109	0.0825
Fishing – demersal, non-destructive low bycatch	Fishing	0.1971	0.0257	0.0394	0.2332	0.2271	0.0153	0.0242	0.1531	0.4229	0.0468	0.0699	0.3374	0.0000	0.0000	0.0000	0.0000
Coastal engineering	Coastal	0.1559	0.0021	0.0136	0.1931	0.7441	0.0052	0.0243	0.1931	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fishing – pelagic, high bycatch	Fishing	0.0995	0.0032	0.0130	0.1784	0.0856	0.0026	0.0119	0.1748	0.0515	0.0030	0.0145	0.2520	0.2950	0.0063	0.0207	0.2039
Fishing - pelagic, low bycatch	Fishing	0.0945	0.0147	0.0201	0.1812	0.1811	0.0108	0.0142	0.1024	0.3359	0.0307	0.0402	0.2172	0.0000	0.0000	0.0000	0.0000
Beach access	Coastal	0.0822	0.0002	0.0032	0.0941	0.7842	0.0006	0.0050	0.0926	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fishing – demersal, non-destructive high bycatch	Fishing	0.0757	0.0369	0.0566	0.3063	0.1510	0.0317	0.0528	0.2917	0.2758	0.0367	0.0606	0.3607	0.3050	0.0577	0.0580	0.2646
Fishing –	Fishing	0.0615	0.0121	0.0246	0.1792	0.1693	0.0229	0.0339	0.1841	0.0000	0.0000	0.0000	0.0000	0.3467	0.0345	0.0310	0.1293

demersal destructive																	
Ocean engineering	Coastal	0.0254	0.0012	0.0126	0.2343	0.0157	0.0019	0.0168	0.2180	0.0111	0.0009	0.0132	0.2652	0.0018	0.0016	0.0140	0.1522
Fishing - recreational	Fishing	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Fish farming	Coastal	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0002	0.0035	0.0998	0.0000	0.0000	0.0000	0.0000
Light pollution	Coastal	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Power plants	Coastal	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sediment runoff	Coastal	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Spatial correlations (R^2) indicate how well each layer predicts overall patterns, while the values for "per-pixel fraction of the total" indicate the relative contribution of each layer to CUI on a per-pixel basis. For details on fishing gear classes, see ref. 59.

Supplementary Table S2. Individual species vulnerability weights across all 24 anthropogenic stressors.

Anthropogenic impacts	Blue whales	Humpback whales	California sea lions	Northern elephant seals	Black-footed albatrosses	Laysan albatrosses	Sooty shearwaters	Leatherback sea turtles
Ocean acidification	12	12	12	12	12	12	12	11
Beach access	0	0	11	11	0	0	0	0
Coastal engineering	0	0	10	10	0	0	0	0
Fishing – demersal destructive	0	0	9.5	9.5	0	0	0	8
Fishing – demersal, non-destructive, high bycatch	0	10*	14*	14*	14*	14*	14*	15*
Fishing – demersal, non-destructive, low bycatch	0	0	9	9	14*	13*	13*	0
Fishing – pelagic, high bycatch	0	10*	13*	13*	13	13	13	15*
Fishing – pelagic, low bycatch	0	10	10	10	13	13	13	0
Fishing – recreational	0	0	0	0	0	0	0	0
Fish farming	8	8	13	8	8	8	8	7
Inorganic pollution	13	13	14	14	15	15	15	13
Invasive species	8	8	8	8	8	8	8	7
Light pollution	0	0	0	0	0	0	0	0
Nutrient runoff	11*	11*	14*	0	14.5	14.5	14.5	6

Ocean deposition	13	13	15	13	16*	16*	16*	13
Ocean engineering	10	10	10	10	9*	9*	9*	0
Ocean-based pollution	15*	15*	15*	15*	17.5*	17.5*	17.5*	16*
Organic pollution	13	14	15	13	17*	17*	17*	13
Power plants	0	0	0	0	0	0	0	0
Sediment runoff	0	0	0	0	0	0	0	0
Shipping	15*	14*	14*	14*	10.5*	10.5*	10.5*	11.5*
Sea surface temperature anomalies	12	16	15	15	15	15	15	10
Coastal waste	15*	16*	15*	15*	16.5*	16.5*	16.5*	12*
Ultraviolet radiation anomalies	14*	14*	11	11	11	11	11	12*

Higher numbers indicate greater impacts. Astericks (*) indicates a direct impact. See Halpern et al. 2009 for a detailed description of data layers.

Supplementary Table S3. Summary of electronic tagging data and IUCN status by species.

Common name	Scientific name	IUCN status*	Tagging location	N Tags	Days	Mean length (days)	Max length (days)	Start date	End date
Blue whales	*Balaenoptera musculus*	Endangered	Central and southern California	37	4188	113	505	7/29/04	8/5/07
Humpback whales	*Megaptera novaeangliae*	Least concern	Northern and central California	13	663	51	108	7/29/04	1/6/06
California sea lions	*Zalophus californianus*	Least concern	Channel Islands and Monterey Bay California	110	6653	60	236	6/4/03	1/26/09
Northern elephant seals	*Mirounga angustirostris*	Least concern	Año Nuevo State Reserve, California and San Benitos, Mexico	224	39581	140	302	6/9/03	5/13/08
Black-footed albatrosses	*Phoebastria nigripes*	Vulnerable	Tern Island, Hawaii	143	2162	15	28	12/19/02	12/5/06
Laysan albatrosses	*Phoebastria immutabilis*	Near threatened	Isla Guadalupe, Mexico	122	676	6	25	1/20/03	3/10/06
Sooty shearwaters	*Puffinus griseus*	Near threatened	New Zealand	18	4654	259	301	1/28/05	12/1/05
Leatherback sea turtles	*Dermochelys coriacea*	Critically endangered	Central California	18	1813	101	323	9/6/04	12/13/08

*IUCN 2012

Supplementary Table S4. Summary of vulnerability measures used to determine the weightings for impact scores across species.

Vulnerability Measure	Category	Rank	Descriptive Notes	Example
Frequency	Never	0		
What is the frequency of the impact?	Rare	1	Infrequent enough to affect long-term dynamics or **population**	Large oil spill
	Occasional	2	Frequent but irregular in nature	Toxic algal blooms
	Annual or regular	3	Frequent and often seasonal or periodic in nature	Runoff events due to seasonal rains
	Persistent	4	More or less constant year-round lasting through multiple years or decades	Persistent hypoxic zones
Direct/Indirect impact	No impact	0		
What's the mechanism by which it is affecting the **individual?**	Distant indirect impact	1	Effects are more than one degree removed	Trophic cascade, food source; ecosystem degradation; impacts something that impacts prey
	Indirect impact	2	Known to cause impact as a result of an indirect link such as via prey; metabolic or life span effect	Impacts prey, impacts of heavy metals that don't result in direct death
	Direct impact	3	Mortality	Bycatch in fishing gear
Resistance (Likelihood of mortality)	No impact	0		
How likely is that impact to affect the **individual**?	Low	1	Unlikely to result in mortality (0-33%)	Anthropogenic noise
	Medium	2	Moderate likelihood of mortality (33-66%)	Domoic acid
	Low	3	High likelihood of mortality (66-100%)	Large reduction in forage base
Recovery time of individual (years)	no impact	0		

Vulnerability Measure	Category	Rank	Descriptive Notes	Example
How long does it take the individual to recover from exposure to the impact?	<1	1		
	1-10	2		
	10-100	3		
	>100	4		
Reproductive Impacts	No impact	0		
What is the level of impact on reproduction of an individual?	Low	1	Impacts some aspect (e.g. behavior) but no loss of reproductive capacity	Temporary displacement from feeding ground
	Moderate	2	Decreased reproductive capacity	Changes in SST result in decrease forage species and reduced reproduction
	High	3	Direct mortality	Death of animal resulting in no repro
Population Effects	No impact	0		
How are the impact distributed across the population?	Low	1	Effects one animal at a time	Ship strike
	Moderate	2	Effects specific sectors or large portion of the population	Impacts females only
	High	3	Effects entire population in CCS	Changes in SST reducing forage species

Supplementary Note 1. ***Impact Summaries***

Ocean acidification
Ocean acidification has been documented as widespread and persistent, and impacts are known to occur in relation to the prey of a number of apex predators (i.e. krill, fish, mollusks, gelatinous prey[61-63]. Additionally, changes in ocean chemistry will increase sound absorption and anthropogenic ocean noise impacting the ability of blue whales to communicate[64-66]. Despite impacts to the entire food chain[67] direct impacts on apex predators are uncertain though impacts are likely to influence the entire population[62,68].

Sea surface temperature anomalies
Climate change affects sea surface temperatures, increases frequency and extremity of El Niño events intensity and timing of upwelling, and changes the distribution and abundance of the prey of pelagic predators[69-78]. This reduction in prey causes shifts in predator distributions, sometimes up to several hundred kilometers[79-82] and thus decreases reproductive capacity and ultimately population levels, particularly for seabirds and sea lions[72,83-87]. Strong El Niños and sea level rise also result in a reduction in available breeding habitat, particularly for elephant seals[80]. While populations generally do recover from El Niño events, recovery time varies depending on the intensity, duration and frequency of El Niño events, and also varies by species with central place foragers being more susceptible because their ranges are reduced[76,88-90].

Organic and Inorganic Pollution
For both egg laying species (sea turtles and seabirds) and mammals, contaminant loads are passed from females to chicks, pups or calves, and increased organic and inorganic pollutant loads result in decreased hatchability and potential mortality in seabird chicks[91-95]. The impacts of heavy metals such as mercury, lead and cadmium on seabirds have been well studied. They are known to cause decreased reproductive success, such as decreased egg size, egg shell thinning, testicular damage, changes in feeding behavior and delayed parental and sibling recognition, in addition to other impacts such as impaired thermoregulation, depth perception and locomotion[96-99]. For mammals, organic and inorganic pollutants have been shown to result in immunosuppression and impacts to the reproductive and endocrine systems, particularly for females[100-107]. In pinnipeds, heavy metal toxicity increases domoic acid poisoning, decreases reproductive capacity, including premature death in pups; similar impacts are suspected for other marine mammals[103,108-110].

Ocean-Based Pollution
Ocean-based pollution in the form of discharge from ships or large-scale oil spills can impact all predator species but has perhaps the greatest impacts on seabirds[111-113]. Oiled birds can lose flight capability in addition to wasting fat and muscle tissues, abnormal conditions in the lungs, kidneys and other organs from even small amounts of exposure to oil slicks[97,114,115].

For leatherback sea turtles and some marine mammals, even moderate exposure to oil may result in impacts to the skin, blood, digestive systems and salt glands, or changes in behavior and thermoregulatory abilities[116-118].

Coastal Waste
Coastal waste, in the form of plastics and other materials, originates primarily from land rather than marine vessels. For all species, ingestion of plastic can result in death from impaction or entanglement, and even smaller amounts of plastic in the gut can result in decreased nutrient absorption, which may be particularly important for leatherbacks because they consume a low nutrient diet[119-127]. While plastic ingestion may also exposes some animals to increased organic pollutants due to the chemicals used to make plastics, the ingestion risks are greatest for procellariform birds (albatrosses, shearwaters and petrels) because they cannot regurgitate like other birds[124].

Shipping
Impacts on marine mammals and sea turtles from shipping occur in the form of ship strikes[128,129]. Though rare for most species, this impact is of particular concern to even the largest whales that are killed as a result of ship strikes[130-132]. Studies in the North Atlantic have shown that over 40% of right whale mortalities are attributable to ship strikes[133]. Seabirds are attracted to ship lights at night and are killed or injured when they strike parts of the ship[134], though this has not been well studied in the California Current region.

Beach Access and Coastal Engineering
Pinnipeds are the only species that come to shore, and are impacted by humans accessing beaches or coastal engineering, largely during the breeding and molting seasons. While these impacts are unlikely to cause long-term impacts, disturbance by humans during the breeding season may result stampedes endangering the young or changes in maternal behavior that reduce provisioning of young[80,90,135,136].

Invasive Species
Impacts of invasive species on pelagic predators in the California Current System are largely unknown, although invasive species cause changes to overall ecosystem health and structure that likely have indirect impacts on predators[137].

Aquaculture
Aquaculture operations result in changes to overall ecosystem health and structure due to increased nutrient inputs and pollution, causing indirect impacts on pelagic predators, particularly by changes in California sea lion feeding habits, especially males[138]. In some instances, sea lions are killed when they poach from aquaculture operations, though this percentage is low.

Nutrient Run-Off
High levels of nutrient run-off, largely from domestic sewage, result in increased algal blooms, including hazardous blooms such as those producing domoic acid that impacts seabirds and marine mammals[139,140]. Domoic acid toxicity results in death for half of the California sea lions treated after stranding, and a reduction in their ability to care for young[101,141]. Similarly, domoic acid poisoning in seabirds results in reduced reproductive capacity due to illness, death or neurological effects[141].

Ocean Engineering
Noise from oil rigs can occasionally alter the behavior of some marine mammal species, such as pinnipeds[142,143]. Seabirds may be attracted to rigs, particularly at night when bright lights are disorienting and they are injured or killed by striking hard surfaces[144].

UV Radiation
Exposure to UV radiation has both direct and indirect impacts on marine predators. UV radiation can result in an increase in the severity of skin lesions, as well as impacts on forage species[145,146]. Increased UV radiation exposure causes reduced productivity through increased mutation rates in phytoplankton, macroalgae, eggs, and larval stages of fish and other aquatic animals[145].

Demersal Fishing
Demersal fishing has both direct and indirect impacts on marine predators. Destructive fishing practices reduce habitat for forage species and reduce prey availability. Many demersal fisheries compete with predators, particularly pinnipeds, for prey species such as rockfish[147-151]. Demersal fisheries for halibut and angel shark use set nets and have appreciable bycatchs of seabirds, pinnipeds and occasional whales and sea turtles[152,153].

Pelagic Fishing
Resource competition occurs with pelagic fishing, particularly between salmon fisheries and California sea lions and seabirds, especially during times of reduced environmental productivity[149,150,154]. Bycatch of predators in most pelagic fisheries occurs but has been significantly reduced by closures and the application of conservation technologies, except the swordfish drift gillnet fishery where occasional bycatch of pinnipeds continues[125,153].

Supplementary References

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