Table S1. Pressures influencing changes in the state of surface-canopy forming kelp habitats are presented, following the Driver-Activity-Pressure-State-Impact-Response (DAPSIR) framework, commonly used to develop management responses to observed changes in marine ecosystems that address human needs (Oesterwind, Rau, and Zaiko 2016; Elliott et al. 2017; Bryhn et al. 2020). Drivers refer to the social and economic drivers of human needs, which are met through specific human activities that pressure ecosystem state change. This table groups pressures by primary activities known to affect kelp forest ecosystems. The pressures are the mechanisms of state change on the natural systems which then lead to impacts on human welfare and responses through specific management measures (sensu Elliott et al. 2017). We've categorized pressures into the spatial and temporal scales that they operate on. We consider changes in the state of kelp habitats as any change in the distribution, abundance and health of canopy-forming kelp, with specific focus on studies from **the Northeast Pacific (bolded references)**.

Activity*: Humans activities related to climate change (e.g. operating oil/gas installations, power stations, industrial/urban emissions)*				
Pressure	**Operating Spatial Scale**	**Operating Temporal Scale**	**State change in kelp forests**	**Reference studies**
Increases in frequency and intensity of marine heatwaves	*regional to global*	*weeks to months*	High ocean temperatures have been associated with declines in kelp forest distribution and abundance.	**Tegner & Dayton, 1991; Tegner *et al.*, 1997; Edwards, 2004; Edwards & G. Hernández-Carmona 2005; Edwards and Estes 2006; Arafeh-Dalmau *et al.*, 2019; Starko *et al.*, 2019; Cavanaugh *et al.*, 2019; Rogers-Bennett & Catton, 2019; Beas-Luna *et al.*, 2020; Sánchez-Barredo *et al.*, 2020; Berry *et al.*, 2020**; **Schroeder et al. 2020 McPherson et al 2021; Smith et al 2021**; Smale, 2020 (Global)
Changes in upwelling patterns	*local-regional*	*weeks to months*	Strong upwelling brings cool nutrient rich water that promotes growth and reproduction, while lower nutrient availability, in particular nitrate (NO3-), coincides with reduced growth, reproduction, survival, and abundance of kelp. Upwelling and other climate fluctuations also impact urchin recruitment, which can influence grazing pressure on kelp	**Wheeler *et al.*, 1984; Zimmerman & Robertson, 1985; Hernández-Carmona *et al.*, 2001; Valdez *et al.*, 2003; Pfister *et al.*, 2018; Hamilton *et al.*, 2020; Berry *et al.*, 2020;Okamato et al. 2020** Wernberg *et al.*, 2019 (Global)

Ocean acidification: changes in pH, pC02 and alkalinity	*regional-global*	*years to decades*	Variation among macroalgae species based on carbon utilization strategy, but non-calcifying seaweeds generally respond positively to increasing global CO2 concentrations	Kroeker *et al.*, 2010; Harley *et al.*, 2012 (Global); Olischläger *et al.*, 2012 (Germany); Hepburn *et al.*, 2011; Leal *et al.*, 2017; Roleda *et al.*, 2012 (New Zealand); Xu *et al.*, 2019 (China)
	local	*years to decades*	Kelp forest can act as a refugia to acidification and deoxygenation by locally elevating pH and DO. Kelp forests can also mitigate ocean acidification by increasing seawater pH, oxygen and aragonite saturation state, and decreasing seawater inorganic carbon content and total alkalinity.	**Frieder *et al.*, 2012; Leary *et al.*, 2017; Pfister *et al.*, 2019**
Salinity change from melting of glaciers, ice caps and ice sheets	*local-global*	*years to decades*	Lower salinity inhibits kelp growth and survival	**Druehl, 1970;** Assis *et al.*, 2018 (North Atlantic)
Change in storm severity and wave exposure	*local-global*	*years to decades*	Increases in the frequency and intensity of storms can lead to breakage and dislodgement of kelp.	**Dayton & Tegner, 1984; Ebeling et al. 1985; Reed et al., 2011; Krumhansl et al., 2016**; **Byrnes et al. 2011**
***Activity**: Construction of in-water structures, replacement of natural substratum, dredging*				
Pressure	**Operating Spatial Scale**	**Operating Temporal Scale**	**State change in kelp forests**	**Reference studies**
Substratum loss or limitation	*local*	*days to years*	Physical removal or degradation of hard substrate decreases kelp abundance	Lawrence, 2014; **Gregr *et al.*, 2019; Schroeder *et al.*, 2020; Torres-Moye & Escofet 2014;** Fowler-Walker & Connell 2007

Changes in water motion & flow rates associated with physical change	*local-regional*	*hours to days*	Kelp nutrient uptake, gas exchange, and reproduction dispersal can decrease without sufficient water motion. Extremely high currents and wave action cause kelp dislodgement and breakage. Changes in flow rate can induce change in kelp morphology	**Hurd *et al.*, 1996; Denny & Cowen, 1997; Duggins *et al.*, 2001; Koehl *et al.*, 2008; Schroeder *et al.*, 2020; Starko *et al.*, 2019; Berry *et al.*, 2020;** Hepburn *et al.*, 2007 (New Zealand); Hurd, 2017 (Global)
Activity: *Coastal development and land use change, including changes in watershed inputs to the ocean*				
Pressure	**Operating Spatial Scale**	**Operating Temporal Scale**	**State change in kelp forests**	**Reference studies**
Changes in water column sediment concentration, e.g. sediment runoff, dredging	*local-regional*	*days to weeks*	Increased sediment particles in the water column can lead to lower sporophyte densities, plus physical scouring and reduced recruitment of kelp gametophytes	**Shaffer & Parks, 1994; Dayton *et al.*, 1984**
			Light limitation from water turbidity and sedimentation reduces kelp growth at gametophyte and young sporophyte phases, potentially inhibiting recruitment	**Vadas, 1972; Devinny & Volse, 1978; Torres-Moye & Escofet, 2014; Traiger & Konar, 2017; Sánchez-Barredo *et al.*, 2020;** Lyngby & Mortensen, 1996 (Denmark); Airoldi & Cinelli, 1997 (Italy)
Eutrophication of coastal zone from nutrient runoff	*local-regional*	*days to weeks*	Increases in epiphyte growth and phytoplankton blooms can lead to decreased kelp health	Russell *et al.*, 2005 (Australia)
Pollution and marine wastes	*local-regional*	*weeks to years*	Exposure to pollutants such as copper and petroleum decreases germling growth rates and gametophyte development	**Antrim *et al.*, 1995**; Leal *et al.*, 2018 (New Zealand)
Point source thermal change, e.g. outflow from power plants	*local*	*weeks to years*	Increased temperature can cause local dieback of kelp and increase the amount of kelp epiphytes	**Dixon *et al.*, 1981; Schiel *et al.*, 2004**
Activity: *Human harvesting of marine mammals, fish, and invertebrates*				

Pressure	Operating Spatial Scale	Operating Temporal Scale	State change in kelp forests	Reference studies
Selective extraction of species	*local-regional*	*years to decades*	Targeted species loss of predators, such as sea otters, fishes, and invertebrates, cause shifts in grazer behavior or survival and density, increasing grazing rates, which can cause regime shifts from productive kelp forests to urchin barrens.	**Estes & Palmisano, 1974; Breen et al., 1982; Watson & Estes, 2011; Beas-Luna & Ladah, 2014; Hamilton and Caselle, 2015; Burt et al., 2018; Rogers-Bennett & Catton, 2019; Smith et al 2021; McPherson et al 2021.**
Bottom trawling bycatch	*local-regional*	*weeks to years*	Direct removal of kelp and indirect smothering from increased sediment	Žuljević *et al.*, 2016 (Adriatic Sea); Christie et al., 1998 (Norway)
Activity: *Human activities/climate change leading to movement of species beyond their natural ranges or collapse within their range*				
Pressure	**Operating Spatial Scale**	**Operating Temporal Scale**	**State change in kelp forests**	**Reference studies**
Introduction of non-indigenous species and translocations	*regional*	*years to decades*	Competition for space from invasive macroalgae & shading by invasive epiphytes and epifauna (e.g. bryozoans) can cause declines in kelp abundance	**(Cogdell & Thornber, 2008, *Undaria pinnatifida*); Sullaway & Edwards, 2020, (*Sargassum honeri*); Dixon *et al.*, 1981b, (*Membranipora membranacea*) Ambrose & Nelson, 1982, *Sargassum muticum*)**
Sea star wasting disease	*local-regional*	*years*	Removal of sea stars from kelp food webs can augment urchin grazing of kelps (i.e. *Pycnopodia* sea stars are urchin predators)	**Harold & Pearse, 1987; Schultz *et al.*, 2016; Burt *et al.*, 2018; Rogers-Bennett & Catton, 2019**
Urchin diseases (local-regional)	*local-regional*	*years*	Removal of sea urchins decreases grazing pressure on kelp, and increases kelp abundance and distribution	**Pearse & Hines, 1979;** Feehan & Scheibling, 2014 (Global)
Activity: *Kelp harvesting, fishing and aquaculture*				

Pressure	Operating Spatial Scale	Operating Temporal Scale	State change in kelp forests	Reference studies
Removal of kelp biomass from natural populations	*local*	*weeks to years*	Harvest of *Macrocystis* canopy appears to have minimal effects on survival, biomass, and growth, although repeated removals may lead to reduced holdfast growth. Complete harvest of kelp can limit recolonization and reduces ecosystem services provided by kelp	**Coon & Roland, 1980; Krumhansl *et al.*, 2017;** Lorentsen *et al.*, 2010 (Norway); Messieh *et al.*, 1991 (Eastern Canada)

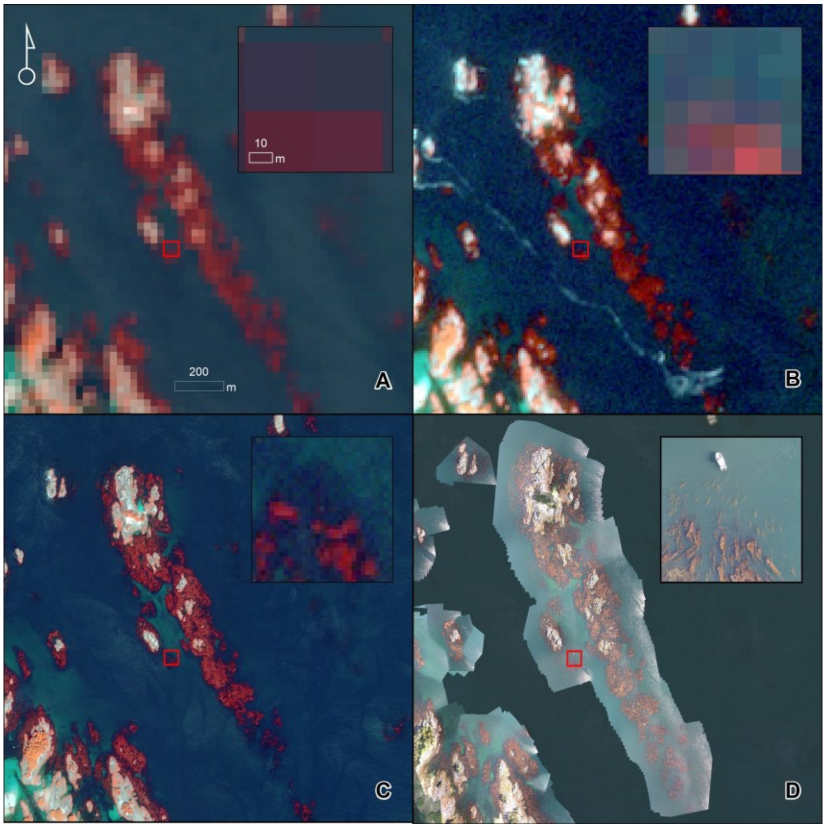

Figure S1. False color images (near-infrared displayed as red) of a kelp forest off the coast of British Colombia: (A) Landsat 30 m, (B) Sentinel 2 (10 m), (C) WordView-2 (2 m), (D) RGB UAS (0.035 m).

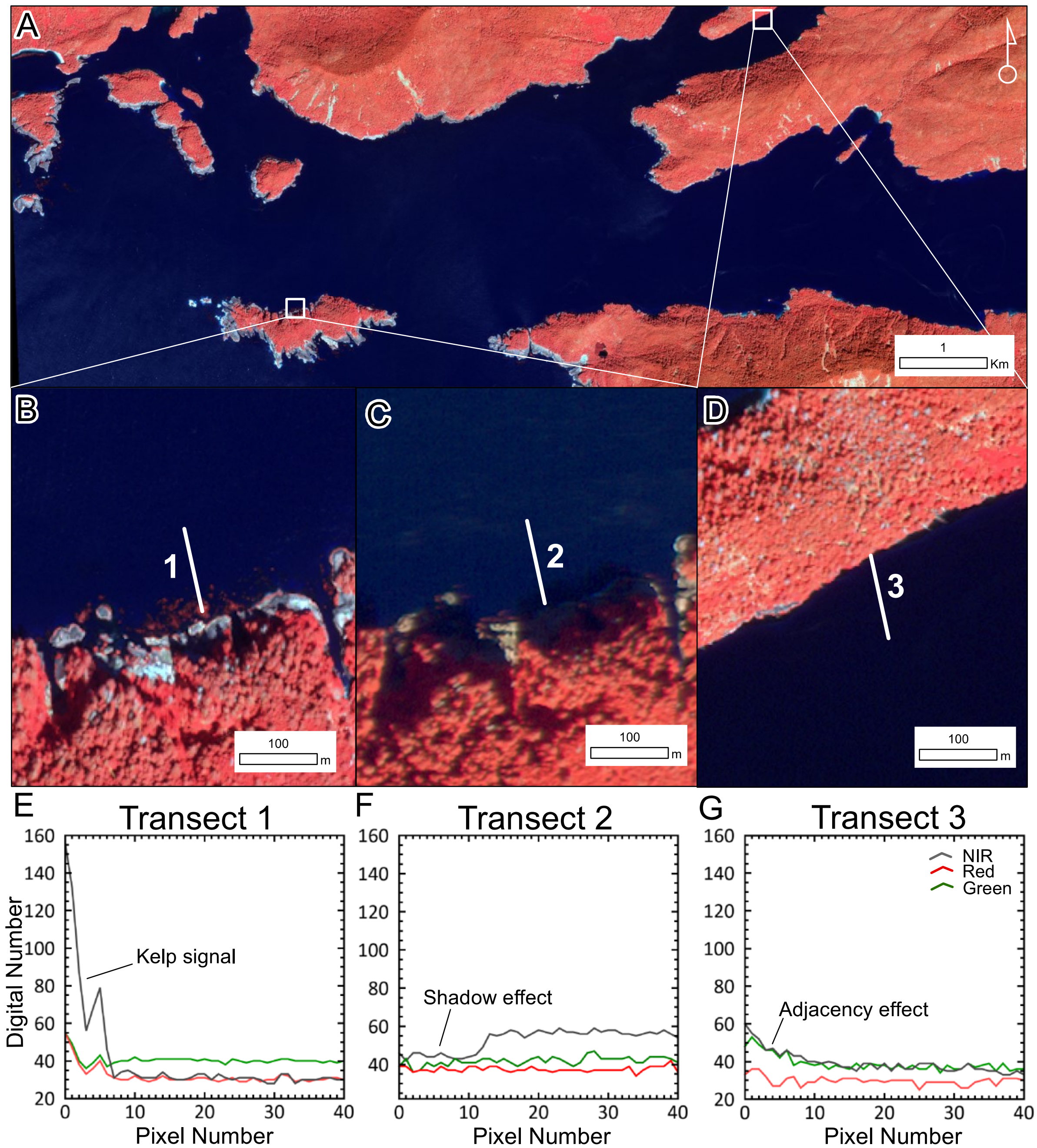

Figure S2. Examples of the impacts of coastal shadowing and adjacency effects. Multispectral (1.84 m) false-color infrared WorldView-2 imagery acquired at different sun elevations depicting some of the factors described in Table 1. (A) Overview of transect locations marked in white boxes. (B) Imagery acquired at a sun elevation of ~58° resulting in no shadow with (E) Transect 1 showing a normal kelp signal with high near infrared reflectance, and relative lower red and green reflectance. (C) Imagery acquired at a sun elevation of ~45° resulting in shadow with (F) Transect 2 showing the dampening of the kelp reflectance signal of pixels adjacent to the shore. (D) Imagery acquired at a sun elevation of ~58° resulting in the adjacency effect where (G) Transect 3 shows the increased reflectance signal from water as a result of contribution of high light scattering from land vegetation to the adjacent water pixels, resulting in possible misclassification of water as kelp. For (E-F) transect pixels are ordered from coastline to offshore

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