

Sea surface and seafloor irradiance

Overview: Sea surface and seafloor irradiance were recorded once or twice per minute in permanent plots at five subtidal reefs and one coastal location off Santa Barbara, California as part of a long-term experiment designed to evaluate the effects of disturbance to giant kelp on the structure and productivity of the benthic community.

Study Sites: Time series data of reef biota (i.e., algae, invertebrates and fish), detrital accumulation, substrate type and topography, and surface and seafloor irradiance were collected at five reefs as part of a long-term experiment designed to evaluate the effects of disturbance to giant kelp (*Macrocystis pyrifera*) on the structure and productivity of the kelp forest community of algae, invertebrates and fishes. The five reefs (Arroyo Quemado 34° 28.048'N, 120° 07.031'W; Carpinteria 34° 23.474'N, 119° 32.510'W; Isla Vista 34° 23.275'N, 119° 32.792'W; Mohawk 34° 23.649'N, 119° 43.762'W; and Naples 34° 25.342'N, 119° 57.102'W) ranged in depth from 5.8 m to 8.9 m (MLLW) and were chosen to represent a range of physical and biological characteristics known to influence the structure and productivity of subtidal reef communities in the region. A ubiquitous (but not always persistent) feature on these reefs was the presence of giant kelp, which forms a dense canopy at the sea surface that alters the biomass, diversity and temporal stability of reef biota (Castorani et al. 2018, Miller et al. 2018, Lamy et al. 2020).

Beginning in 2008, giant kelp was removed once per year in winter from a 40 m x 50 m plot at three reefs (Arroyo Quemado, Carpinteria, and Naples) and a 30 m x 50 m plot at one reef (Mohawk) to simulate the effects of winter storm disturbance (referred to as “annual removal” treatment). An adjacent unmanipulated 40 m x 50 m plot at each site served as a control. Beginning in winter 2010, giant kelp was removed 1 to 2 times each season in a 10 m x 50 m area within (or in the case of Mohawk adjacent to) each of the annual removal plots to create a “continual removal” treatment. In fall 2011, a fifth site was established at Isla Vista with paired 40 m x 50 m annual removal and control plots (a 50 m x 10 m continual removal treatment was not established at this site). The reef community of algae (including giant kelp), invertebrates and fish were surveyed in annual removal and continual removal plots prior to each experimental removal of giant kelp. Thus, data collected on the date following the first kelp removal represents the first sampling period of the annual and continual removal treatments. The last experimental removals of giant kelp occurred in winter 2016 or winter 2017, depending on the site. The last sampling of reef communities under experimental conditions for annual and continual kelp removal treatments occurred ~12 months following the last kelp removal. Control, annual removal, and continuous removal plots continued to be sampled seasonally through spring 2023 to document the recovery of the reef community in the absence of experimental kelp removal. Dates of the initiation and cessation of kelp removal in the experimental plots are provided in Table 1.

Table 1: Dates (format yyyy/mm/dd) of the first and last experimental kelp removal for the annual and continual giant kelp removal treatments at the five reef sites.

Reef	Transect	Treatment	Date of First Removal	Date of Last Removal
Arroyo Quemado	7	Annual	2008/01/30	2017/03/02
	8	Continual	2010/02/04	2017/03/02
Carpinteria	9	Annual	2008/02/12	2017/02/15
	10	Continual	2010/01/29	2017/02/15
Isla Vista	4	Annual	2011/10/26	2016/02/18
Mohawk	3	Annual	2008/01/17	2017/02/13
	4	Continual	2010/05/05	2017/02/13
Naples	9	Annual	2008/01/10	2016/02/09
	10	Continual	2010/01/28	2016/02/09

Irradiance was measured using submersible spherical PAR sensors (MKV-L, Alec Electronics, Japan) from 2008-2015 and submersible planar PAR sensors (DEFI-L, Alec Electronics, Japan) from 2016 to the present. Sensors were deployed at each of the five control transects and at least one experimental transect from the experiment start to present (Table 2). Measurements were averaged over the course of each hour and data are presented as average instantaneous irradiance per hour in units of $\mu\text{mol m}^{-2} \text{sec}^{-1}$.

Table 2: Chronology of PAR sensor deployments for the experimental treatments at the five reef sites of the long-term kelp removal experiment

Reef	Transect	Period of PAR sensor deployment
Arroyo Quemado	4	01/30/2008 - present
	7	01/30/2008 – 08/09/2010, 05/08/2017 - present
	8	08/09/2010 – 05/18/2017
Carpinteria	7	01/11/2008 - present
	9	01/11/2008 – 09/03/2010, 05/19/2017 - present
	10	09/03/2010 – 08/10/2017
Isla Vista	3	01/19/2012 - present
	4	01/19/2012 - present
Mohawk	2	10/16/2008 - present
	3	10/16/2008 - present
	4	06/14/2010 – present
Naples	3	01/30/2008 - present
	9	01/30/2008 - 05/16/2017 - present
	10	NA

Measurements of seafloor irradiance: PAR sensors were mounted ~ 30 cm off the bottom on rebar stakes using stainless steel hose clamps. Sensors were retrieved for data download and servicing every 6-12 weeks and simultaneously replaced with newly serviced sensors. Sensors were wrapped in black electrical tape during transport from the laboratory to the field to ensure that all light readings prior to deployment were zero. Once deployed underwater the tape was removed and the time of deployment noted in an event log.

Biological fouling (primarily by benthic diatoms) on the sensors occurs to varying degrees during deployment which affects measurement accuracy. To account for attenuation of light due to biofouling we cleaned the sensors in situ 20 minutes before retrieval and calculated attenuation (a) by biofouling as

$$(a) = -\ln\left(\frac{\text{dirty}}{\text{clean}}\right)$$

where *dirty* represents the mean irradiance sampled once per minute for 20 minutes prior to the sensor being cleaned on retrieval day, and *clean* represents the mean irradiance sampled once per minute for 20 minutes immediately after cleaning. The effects of biofouling on irradiance were assessed by comparing mean dirty and mean clean irradiance using a student's t-test with $\alpha = 0.05$. Irradiance values from significantly fouled sensors were corrected on each day of the deployment using the equation:

$$\text{Corrected irradiance} = \text{Measured irradiance} * \exp\left(\frac{a}{\sum d}\right) * t$$

Here, a represents attenuation due to fouling as described above, d represent the total number of days since deployment (over which we assume the fouling accumulated), and t represents the number of days that have passed since deployment for the set of values being corrected (Harrer et al. 2013).

Discontinuation of the MKV-L spherical sensors led us to switch to the DEFI-L planar sensors, which record lower values of seafloor irradiance (particularly at low light levels) because they measure light over a narrower optical field. We used data (see data package <https://portal-s.edirepository.org/nis/mapbrowse?scope=knb-lter-sbc&identifier=128>) collected during simultaneous deployments of paired MKV-L and DEFI-L sensors to develop algorithms to convert all values recorded from planar sensors to values representative of spherical sensors by curve fitting for the parameters A , t_1 and y in the equation of Long et al. 2012:

$$\text{Spherical sensor value} = A * e^{-\text{planar sensor value}/t_1} + y$$

Conversions from planar to spherical values were applied to all data collected between 06:00 and 20:00 local time using the equation:

$$\text{Spherical sensor value} = 20000018 * e^{-\text{planar sensor value}/11064484} - 20000000$$

Measurements of sea surface irradiance: From 2008-2015, irradiance was measured from MKV-L and DEFI-L sensors mounted ~30 to 100 cm above the sea surface on a moored vertical spar buoy at three reefs (Arroyo Quemado, Carpinteria and Mohawk). The sensors were calibrated for readings in air by the manufacturer. The time series obtained from these sensors proved difficult to maintain due to sensor damage and loss caused by storms and boat traffic. Because of this and the fact that sea surface irradiance was highly similar among reefs (unpublished data) a single surface sensor was deployed on an unobstructed rooftop at the University of California Santa Barbara beginning in 2016. Sea surface values were not adjusted for biofouling because it did not occur. Similarly, there was no need to convert values of sea surface irradiance obtained from planar sensor to values representative of spherical sensors because irradiance values recorded by the two types of sensors at the sea surface were nearly identical.

References

Castorani, M. C. N., D. C. Reed and R. J. Miller. 2018. Loss of foundation species: disturbance frequency outweighs severity in structuring kelp forest communities. *Ecology*, 99: 2442-2455.

Harrer, S. L., D. C. Reed, R. J. Miller and S. J. Holbrook. 2013. Patterns and controls of the dynamics of net primary production by understory macroalgal assemblages in giant kelp forests. *Journal of Phycology*, 49: 248-257.

Long, M. H., J. E. Rheuban, P. Berg, J. C. Zieman. 2012. A comparison and correction of light intensity loggers to photosynthetically active radiation sensors. *Limnology and Oceanography*, 10: 416 – 424.

Miller, R. J., S. Harrer and D. C. Reed. 2012. Addition of species abundance and performance predicts community primary production of macroalgae. *Oecologia*, 168: 797-806.

Rassweiler, A., D. C. Reed, S. L. Harrer and J. Clint Nelson. 2018. Improved estimates of net primary production, growth, and standing crop of *Macrocystis pyrifera* in Southern California. *Ecology*, 99: 2132.

Reed, D. C. and M. S. Foster. 1984. The Effects of Canopy Shadings on Algal Recruitment and Growth in a Giant Kelp Forest. *Ecology*, 65:937-948.