Kelp Forest Community Biomass Time Series Methods

Overview. Little information exists on the biomass dynamics of taxonomically complex communities of marine plants and animals inhabiting shallow reefs. To address this lack of information we estimated the biomass of benthic species of macroalgae, sessile and mobile macro invertebrates and fish in permanent plots on subtidal reefs off Santa Barbara, California by combining time series data of size-specific density or percent cover with taxon-specific relationships between biomass and size for solitary taxa and between biomass and percent cover for taxa that are difficult to distinguish as individuals.

Study Sites. Time series data of reef biota (i.e., algae, invertebrates and fish) and 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 benthic community. The five reefs (Arroyo Quemado 34^0 28.048'N, 120^0 07.031'W; Carpinteria 34^0 23.474'N, 119^0 32.510'W; Isla Vista 34^0 23.275'N, 119^0 32.792'W; Mohawk 34^0 23.649'N, 119^0 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 from a 2000 m^2 plot once per year in winter at four reefs (Arroyo Quemado, Carpinteria, Mohawk and Naples) to simulate the effects of winter storm disturbance (referred to as "annual removal" treatment). An adjacent unmanipulated 2000 m^2 plot served as a control. Beginning in winter 2010, giant kelp was removed 1 to 2 times per season within a 600 m^2 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 2000 m^2 annual removal and control plots (a 600 m^2 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 continue to be sampled seasonally 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, in the format yyyy/mm/dd, of the first and last kelp removal for the annual and continual giant kelp removal treatments at the five reef sites.

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

Abundance. Divers surveyed the size-specific density or percent cover of benthic macroalgae, sessile and mobile macro invertebrates and fish (cover of algae and sessile invertebrates: https://portal.edirepository.org/nis/mapbrowse?scope=knb-lter-sbc&identifier=28 ; size specific density of algae and invertebrates: https://portal.edirepository.org/nis/mapbrowse?scope=knb-lter-sbc&identifier=34 ; giant kelp: https://portal.edirepository.org/nis/mapbrowse?scope=knb-lter-sbc&identifier=29 ; fish: https://portal.edirepository.org/nis/mapbrowse?scope=knb-lter-sbc&identifier=30) within permanent 40 m x 2 m sampling areas (hereafter referred to as transects) located in the center of each plot twice per season (approximately every six weeks) from January 2008 through December 2012 and once per season (approximately every 12 weeks) beginning in the winter of 2013.

Biomass of Macroalgae.
Time series data of the abundance of all understory species including small *M. pyrifera* (< 1 m in height) were converted to dry mass using -taxon-specific relationships with size-specific density or percent cover developed for 23 taxa that accounted for more than 95% of the standing biomass of understory macroalgae averaged across all sampling locations from 2008 to 2018 (algae biomass relationship data table in https://portal.edirepository.org/nis/mapbrowse?scope=knb-lter-sbc&identifier=127). The

conversion of abundance to mass for less common taxa was done by proxy using the relationship generated for a morphologically similar species (Table 2).

Table 2. List of uncommon taxa of macroalgae recorded in permanent plots and the proxy species used to convert their abundance to biomass.

SP_CODE	GENUS	SPECIES	PROXY SP_CODE	Proxy GENUS	PROXY SPECIES
AMZO	*Amphiroa*	*zonata*	BO	*Bossiella*	*orbigniana*
ANPA	*Anisocladella*	*pacifica*	R	*Rhodymenia*	*californica*
AU	*Acrosorium*	*uncinatum*	CF	*Callophyllis*	*flabellulata*
BLD	Unidentified brown blade	spp.	MPJ	*Macrocystis*	*pyrifera* - < 1m in height
BRA	Branching Red Algae	spp.	R	*Rhodymenia*	*californica*
CAL	*Calliarthron*	*cheilosporioid*	BO	*Bossiella*	*orbigniana*
CG	*Cladophora*	*graminea*	RAT	Red Algal Turf	spp.
COF	Codium	fragile	GS	*Gracilaria*	spp.
CP	*Colpomenia*	spp.	POLA	*Polyneura*	*latissima*
CRYP	*Cryptopleura*	spp.	BF	*Cryptopleura*	*farlowianum*
CZ	*Chondracanthus*	*spinosa*	CC	*Chondracanthus*	spp.
DIAT	Diatom	Mat	EC	Encrusting	coralline
DU	*Dictyopteris*	*undulata*	DP	*Dictyota*	spp.
EC	Encrusting	coralline	EC	Encrusting	coralline
EGJ	*Egregia*	*menziesii*	MPJ	*Macrocystis*	*pyrifera* - < 1m in height
ER	Encrusting	red	EC	Encrusting	coralline
FASP	*Fauchea*	spp.	R	*Rhodymenia*	*californica*
FG	Filamentous green	spp.	FR	Filamentous red	spp.
FTHR	*Neoptilota Ptilota Rhodoptilum*	spp.	CF	*Callophyllis*	*flabellulata*
GEL	*Gelidium*	spp.	GS	*Gracilaria*	spp.
GR	*Gelidium*	*robustum*	GS	*Gracilaria*	spp.
GYSP	*Gymnogongrus*	spp.	R	*Rhodymenia*	*californica*
HAGL	*Halosaccion*	*glandiforme*	POLA	*Polyneura*	*latissima*
IR	*Iridaea*	spp.	CC	*Chondracanthus*	spp.
LI	*Lithothrix*	spp.	CO	*Corallina*	*officinalis*
LX	*Osmundea*	*spectabilis*	LS	*Laurencia*	spp.
NA	*Nienburgia*	*andersoniana*	CF	*Callophyllis*	*flabellulata*
NEO	*Neoagardhiella*	*baileyi*	GS	*Gracilaria*	spp.
PHSE	*Phycodrys*	*setchellii*	R	*Rhodymenia*	*californica*
PHTO	*Phyllospadix*	*torreyi*	DL	*Desmarestia*	*ligulata*
PL	*Prionitis*	*lanceolata*	CC	*Chondracanthus*	spp.

PRSP	*Prionitis*	spp.	CC	*Chondracanthus*	spp.
SAFU	*Sarcodiotheca*	*furcata*	CF	*Callophyllis*	*flabellulata*
SCCA	*Scinaia*	*confusa*	GS	*Gracilaria*	spp.
SELO	*Scytosiphon*	*lomentaria*	DP	*Dictyota*	spp.
STIN	*Stenogramme*	*interrupta*	R	*Rhodymenia*	*californica*
TALE	*Taonia*	*lennebackerae*	DP	*Dictyota*	spp.
UBB	Unidentified brown blade	spp.	BR	Blady red	spp.
UEC	Unidentified erect coralline	spp.	CO	*Corallina*	*officinalis*
UV	*Ulva*	spp.	DP	*Dictyota*	spp.
ZOMA	*Zostera*	*marina*	DL	*Desmarestia*	*ligulata*

Biomass was converted from de-calcified dry mass to units of wet mass and ash free dry mass for all taxa, using proxy taxa when necessary. Dry to wet mass and dry to ash free dry mass conversions are provided. These ratios did not vary substantially among measured taxa and thus those proxy species are not presented here.

Divers also counted the density of *M. pyrifera* fronds $\geq$ 1 m in height in the 40 m x 2 m transects. The density of *M. pyrifera* fronds $\geq$ 1 m in height was converted to the biomass of giant kelp by applying month-specific relationships between frond density (no. m^{-2}) and dry mass density (dry kg m^{-2}) developed by Rassweiler et al. (2018). These relationships allowed us to use our measurements of frond density to estimate total standing biomass of giant kelp in any given month, as well as the individual components of *M. pyrifera* standing biomass, namely: (1) the mass of the surface canopy, (2) the mass of the water column portion of fronds that form a surface canopy, and (3) the mass of young subsurface fronds that have not yet reached the sea surface. The latter is important because the standing biomass *M. pyrifera* consisted entirely of subsurface fronds for at least three months following its removal from our experimental plots. Thus, during the three months following experimental kelp removal we used month-specific relationships between frond density and the mass of subsurface fronds to convert *M. pyrifera* frond density to standing biomass in our experimental kelp removal plots. In all other cases, we assumed a natural distribution of frond sizes in our plots and we estimated *M. pyrifera* biomass using month specific relationships between frond density and total standing biomass.

Biomass of Invertebrates.
Time series data of the abundance of macroinvertebrate species were converted to shell free or decalcified dry mass using taxon-specific relationships with size-specific density or percent cover developed for the 78 most common taxon (invertebrate biomass relationship data table in https://portal.edirepository.org/nis/mapbrowse?scope=knb-lter-sbc&identifier=127). The conversion of abundance to mass for less common invertebrate taxa was done by proxy using the relationship generated for a morphologically similar species Table 3.

Table 3. List of uncommon taxa of benthic invertebrates recorded in permanent plots and the proxy species used to convert their abundance to biomass.

SP_CODE	GENUS	SPECIES	PROXY SP_CODE	PROXY GENUS	PROXY SPECIES
ANSP	*Anthopleura*	spp.	URLO	*Urticina*	*lofotensis*
APVA	*Aplysia*	*vaccaria*	APCA	*Aplysia*	californica
ARUD	*Discophyton*	*rudyi*	PLUM	*Plumularia*	sp.
BOW	*Amathia*	*gracilis*	TC	*Thalamoporella*	*californica*
BRSP	*Barentsia*	sp.	TC	*Thalamoporella*	*californica*
CECO	*Centrostephanus*	*coronatus*	SFL	*Sebastes*	*flavidus*
COST	*Celleporina*	*robertsoniae*	DC	*Diaperoforma*	*californica*
CROC	*Crisia*	*occidentalis*	TC	*Thalamoporella*	*californica*
CUPI	*Cucumaria*	*piperata*	LINU	*Lissothuria*	*nutriens*
ECB	*Bryozoa*	spp.	CESP	*Cellaria*	sp.
HACO	*Haliotis*	*corrugata*	HARU	*Haliotis*	*rufescens*
HACR	*Haliotis*	*cracherodii*	HARU	*Haliotis*	*rufescens*
HADE	*Halcampa*	*decemtentaculata*	HARU	*Haliotis*	*rufescens*
HAKA	*Haliotis*	*kamtschatkana*	HARU	*Haliotis*	*rufescens*
HC	*Acanthancora*	*cyanocrypta*	ES	*Demospongiae*	spp.
HIP	*Primavelans*	*mexicana*	DC	*Diaperoforma*	*californica*
HPAC	*Heteropora*	*pacifica*	DC	*Diaperoforma*	*californica*
LIGS	*Lithopoma*	spp.	LIGL	*Lithopoma*	spp.
MISE	*Metridium*	*dianthus*	CY	*Corynactis*	*californica*
MT	*Jellyella*	*tuberculata*	CESP	*Cellaria*	sp.
MUFR	*Muricea*	*fruticosa*	MUCA	*Muricea*	*californica*
OBSP	*Obelia*	sp.	PLUM	*Plumularia*	sp.
OKL	*Orthasterias*	*koehleri*	PGL	*Pisaster*	*giganteus*
PHOR	*Phoronida*	spp.	SABW	*Sabellidae*	spp.
PHSP	*Phyllactis*	spp.	CY	*Corynactis*	*californica*
PIEL	*Pista*	*elongata*	SABW	*Sabellidae*	spp.
PLAB	*Phidolopora*	*labiata*	DC	*Diaperoforma*	*californica*
SC	*Spheciospongia*	*confoederata*	ES	*Demospongiae*	spp.
UAB	*Bryozoa*	spp.	TC	*Thalamoporella*	*californica*
UM	*Arthropoda*	spp.	ATM	*Amphipoda*	spp.
URPI	*Urticina*	*piscivora*	URLO	*Urticina*	*lofotensis*
WASP	*Phidolopora*	*labiata*	DC	*Diaperoforma*	*californica*

Biomass of Reef Fish.
Time series data of the abundance and size of reef fish (i.e., those observed within 2m of the benthos) was converted to wet mass (g) using species-specific relationships obtained from the literature (fish biomass relationship data table in

https://portal.edirepository.org/nis/mapbrowse?scope=knb-lter-sbc&identifier=127). For some species, relationships were derived for standard length to mass. In these cases, we used information provided from the author to convert measurements of total length to standard length prior to estimating wet mass. The wet mass of bony fishes was converted to de-boned dry mass (g) and ash free dry mass (g) using the average of conversion ratios for all reef fish provided in Taylor (1997). Wet mass of cartilaginous fishes was converted to dry biomass (g) using the conversion factor of Thorson 1976. No information was found to convert wet mass to ash free dry mass for cartilaginous fishes. Published relationships were not available for every fish species encountered on SBC LTER reefs. Therefore, we estimated the biomass of these species by proxy using the relationship published for a morphologically similar species (Table 4).

Table 4. List of reef fish recorded in permanent plots lack a published relationship between size and mass and the proxy species used to convert their abundance to biomass

SP_CODE	**GENUS**	**SPECIES**	**PROXY SP_CODE**	**PROXY GENUS**	**PROXY SPECIES**
AHOL	*Alloclinus*	*holderi*	CLIN	*Gibbonsia*	sp.
BOTH	*Bothid*	spp.	PCAL	*Paralichthys*	*californicus*
CAGG	*Cymatogaster*	*aggregata*	EJAC	*Embiotoca*	*jacksoni*
COTT	*Cottidae*	spp.	CNIC	*Rhinogobiops*	*nicholsii*
CSTI	*Citharichthys*	*stigmaeus*	PCAL	*Paralichthys*	*californicus*
CVEN	*Cephaloscyllium*	*ventriosum*	HEFR	*Heterodontus*	*francisci*
ELAT	*Embiotoca*	*lateralis*	EJAC	*Embiotoca*	*jacksoni*
EMBI	*Embiotoca*	spp.	EJAC	*Embiotoca*	*jacksoni*
HARG	*Hyperprosopon*	*argenteum*	EJAC	*Embiotoca*	*jacksoni*
LHIR	*Leiocottus*	*hirundo*	OPIC	*Oxylebius*	*pictus*
NBLA	*Neoclinus*	*blanchardi*	CNIC	*Rhinogobiops*	*nicholsii*
SCAL	*Squatina*	*californica*	RPRO	*Pseudobatos*	*productus*
SCHR	*Sebastes*	*chrysomelas*	SAUR	*Sebastes*	*auriculatus*
SCSP	*Sebastes*	spp.	SCAR	*Sebastes*	*carnatus*
STRE	*Sebastes*	*serriceps*	SCAR	*Sebastes*	*carnatus*
XCAL	*Haemulon*	*californiensis*	DVAC	*Rhacochilus*	*vacca*

References

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