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Journal: Ecology
Manuscript type: Article

Detrital supply suppresses deforestation to maintain healthy kelp forest ecosystems

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Manuscript received 22 March 2021; revised 29 September 2021; accepted 15 October 2021
Handling Editor: Steven G. Morgan

Open Research: Long-term community data (Santa Barbara Coastal LTER, et al. 2021b) are available from the Environmental Data Initiative at <https://doi.org/10.6073/pasta/f1cf070648d7654ada052835afb2cfe9>, and long-term productivity data (Santa Barbara Coastal LTER, et al. 2021c) are available from the Environmental Data Initiative at <https://doi.org/10.6073/pasta/bf6049d8abc0177c72564ff014b8fe6b>. Mesocosm experiments data (Santa Barbara Coastal LTER, et al. 2021a) are available from the Environmental Data Initiative at <https://doi.org/10.6073/pasta/6af4cc3b0e63b887baf1ae9201e1cd1d>. Code (maerennick et al. 2021) is available in Zenodo at <https://doi.org/10.5281/zenodo.5645471>.

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the [Version of Record](#). Please cite this article as doi: [10.1002/ecy.3673](https://doi.org/10.1002/ecy.3673)

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ABSTRACT

Herbivores can reach extraordinary abundances in many ecosystems. When herbivore abundance is high, heavy grazing can severely defoliate primary producers and, in some cases, even drive ecosystem to undergo regime shifts from a high productivity state to a denuded, low productivity state. While the phenomenon of herbivore-driven regime shifts is well-documented, we only partially understand the mechanisms underlying these events. Here, we combine herbivory experiments with 21 years of long-term monitoring data of kelp forest ecosystems to test the hypothesis that herbivores drive regime shifts when herbivory exceeds primary production. To test this hypothesis, we quantified how the foraging habits of an important group of marine herbivores— sea urchins— changes with increases in sea urchin biomass and triggers regime shifts to a foundation species— giant kelp (*Macrocystis pyrifera*). Using experiments, we quantified how the grazing capacity of urchins increases as urchin biomass increases, then we combined these estimates of urchin grazing capacity with estimates of kelp production to predict when and where urchin grazing capacity exceeded kelp production. When grazing capacity exceeded kelp production, sea urchins caused a 50-fold reduction in giant kelp biomass. Our findings support the hypothesis that the balance between herbivory and production underlies herbivore-driven regime shifts in southern California kelp forests and provides insight into when and where urchins are likely to force regime shifts in kelp forest ecosystems.

Keywords: consumption; density-dependence; detritus; ecosystem transition; herbivore; kelp

INTRODUCTION

Intense foraging by primary consumers can fundamentally alter the structure and function of communities (Silliman et al. 2013). For instance, outbreaks of herbivorous insects can defoliate forests across 1000's of km² (Kautz et al. 2016), grazing by ungulates can denude landscapes (Hopcraft et al. 2012) and predation by sea stars can lead to widespread mortality of reef building corals (Holbrook et al. 2018). In extreme cases, consumers can eliminate the dominant primary producers in a community, reducing productivity and leaving only producers that are resistant to foraging (Augustine and McNaughton 1998). Consumer-driven changes in community structure are often persistent, such that even when consumer abundance decreases, the community remains in an alternative state (Schroder et al. 2005). Yet, high consumer density does not always trigger alternative ecosystem states. Some locations can support high biomass of consumers while others undergo rapid shifts at relatively low consumer biomass. The mechanism underlying variability in when and where consumers drive shifts into alternative community states remains an active area of research. Resolving this context dependency is critical to understanding ecosystem tipping points and to avoid crossing biological thresholds to alternative states which provide fewer services to people and nature.

In principle, consumer-driven shifts to alternative states occur when consumption exceeds resource production. Predicting when and where consumption exceeds production requires an understanding of how consumer foraging behavior and per-capita consumption rates shift with consumer density. The relationship between consumer density and per-capita consumption can take three plausible forms (Klemmer et al. 2012). First, increases in consumer density can have no effect on per-capita consumption, such that the collective consumption rate of a population increases linearly with consumer density (Reice 1991). Second, interference or

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competition among consumers as consumer density increases can cause per-capita consumption to decline. At the population-scale, competition can cause consumption to increase at a decelerating rate with density because competition is weaker at low densities and stronger at high densities (Arditi and Ginzberg 1989, Little et al. 2020, Brook and Bradshaw 2006). Finally, facilitation among consumers can cause per-capita consumption to increase as consumer density increases. In this case, the collective consumption rate of a group might accelerate exponentially or sigmoidally with consumer density (Sommer 1992, McKie et al. 2009). When the relationship between consumer density and per-capita consumption is constant or positive, there is a higher probability that increases in consumer density will cause large reductions in primary producers because consumers are not limited by intraspecific competition. However, the extent to which constant or positive increases in foraging with consumer density are common in consumer-driven disturbances remains unclear, particularly in ecosystems prone to alternative states.

Here, we quantify how the relationship between consumer biomass and consumer foraging rates drives when and where kelp forest ecosystems undergo shifts to alternative states. Temperate rocky reefs characterized by kelp, a group of canopy-forming brown macroalgae that form productive subtidal “forests”, are known to experience abrupt changes from kelp-dominated communities to communities with little to no kelp (Filbee-Dexter and Scheibling 2014, Ling et al. 2015). An important factor causing such state shifts is intensive grazing by sea urchins, which has been linked to massive declines in kelp abundance and the formation of urchin-dominated states, known as urchin barrens, that can persist for decades (Lawrence 1975, Sala et al. 1998, Spindel et al. 2021). Urchin barrens occur on shallow rocky reefs worldwide and are characterized by herbivore-resistant algal species (Ling and Johnson 2009) that display lower net primary productivity and biodiversity than kelp-dominated sites (Steneck et al. 2002). In theory,

kelp deforestation should result when the consumption rate of an urchin population exceeds kelp production. Increases in the consumption rate can occur due to increases in urchin density, such as when top-down control by urchin predators is reduced or urchin recruitment to a site is high. Alternatively, kelp production can vary independent of urchins due to temperature (Wernberg et al. 2016), wave disturbance (Dayton and Tegner 1984, Reed et al. 2011), and nutrient availability (Bell et al. 2015). Across temperate rocky reefs, kelp abundance can be high even when urchin abundance is high and changes in urchin abundance do not result in proportional declines in kelp (Ling et al. 2015), suggesting that when and where urchins deforest kelp communities depends on the balance between kelp production and how much kelp urchins consume at a given urchin biomass.

One longstanding hypothesis for why urchin populations switch from coexisting with kelp to deforesting kelp is a shift in foraging behavior (Harrold and Reed 1985). Urchins are notably omnivorous, foraging on kelp, pieces of kelp detached from the substrate (e.g. detritus), other algal species, invertebrates (ex. salps or tubeworms, Duggins 1981, Spindel et al 2021), or calcareous reef structures (Rasher et al. 2020). The leading hypothesis is that urchins passively forage on kelp detritus until a change in kelp production causes urchins to actively graze canopy-forming kelps attached to the substrate (*hereafter* “standing” kelp, *sensu* Kriegisch et al. 2019). However, variation in urchin foraging rates with changes in urchin biomass could interact with shifts in the availability of detritus to result in kelp deforestation. For instance, if urchin foraging rates are invariant with urchin biomass and urchin biomass is high, then slight declines in detrital production in a kelp community could cause urchins to actively graze standing kelp. Yet, if urchins increase their per-capita feeding rates through facilitation— as may occur in grazing

fronts (Dean et al. 1984, Ling et al. 2019)— then small changes in urchin biomass at a threshold might result in deforestation without a change in detrital production.

In this study, we test how the relationship between density-dependent foraging rates and primary production alters a community's resistance to consumer-driven changes in community state using California rocky reefs dominated by *Macrocystis pyrifera* (hereafter, “kelp”) as a model system. We first investigated how the foraging rate of urchins varies with urchin biomass using mesocosm foraging experiments. We coupled these experimental results with 21 years of spatially explicit data on kelp community dynamics to hindcast rates of detrital production and consumption. Finally, we tested the long-standing hypothesis that production of kelp detritus suppresses deforestation by quantifying how the relationship between detrital supply and predicted urchin consumption alters the dynamics of standing kelp biomass. Our results confirm that the balance between detrital supply and urchin foraging mediates alternative states on temperate rocky reefs and builds a mechanistic understanding of how density-dependent foraging and primary production can interact to cause consumer-driven disturbances.

METHODS

Grazing experiment: How does foraging rate vary with urchin biomass?

We conducted laboratory mesocosm experiments during May-August 2019 to estimate detrital kelp grazing rates by red (*Mesocentrotus franciscanus*) and purple (*Strongylocentrotus purpuratus*) sea urchins across ranges of urchin biomass that spanned kelp- and urchin-dominated ecosystem states. To select density treatments, we characterized purple and red urchin densities in the Santa Barbara Channel, using 21 years of observational data collected by the Santa Barbara Coastal Long-term Ecological Research program (SBC LTER, *see section*

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“Observational data” for details). Based on the resulting density ranges, we selected eight abundances for purple urchins (2, 3, 7, 11, 19, 22, 24, 44 individuals arena⁻¹; 1.6 m² arena) and six abundances for red urchins (1, 2, 3, 5, 7, 12 individuals arena⁻¹). We collected urchins of varying size using SCUBA from coastal kelp forests in the Santa Barbara Channel (California, USA), such that the collected pool of urchins approximated the 95% confidence intervals of the observed size frequency distribution of each species (Appendix S1: Fig. S1). To assign urchins into density treatments, we drew from the pool of collected urchins so that urchin size varied randomly, and then measured the wet weight of each urchin (± 0.1 g) to calculate the total biomass in a trial. Total biomass in trials ranged from 63.6 – 1851.9 g·m⁻² for purple urchins and 90.7-1771.3 g·m⁻² for red urchins. These ranges included the Ling et al. (2015) threshold associated with nonlinear reductions in macroalgae (668 ± 115 g·m⁻²), and approached the maximum urchin biomass observed at local urchin-dominated sites (2038 g·m⁻²).

We maintained experimental urchins in 400L laboratory mesocosms with a continuous flow of ambient seawater at ~ 7 L min⁻¹ (14.5 ± 0.01 °C, $\bar{X} \pm SE$ unless other specified). We divided mesocosms into two experimental units separated by a permeable barrier, resulting in 37 arenas with 1.6 m² of accessible surface space (submerged vertical walls and bottom) for urchins. In preliminary trials the barrier did not lead to differences in oxygen saturation or temperature and we found no evidence for systematic differences in foraging rates by tank side (Tukey’s *post hoc*: $p > 0.05$ for all comparisons).

Over a 9-week period, we conducted foraging trials to specifically estimate urchin foraging rates on mature kelp blades. Kelp detritus available to urchins in natural settings can consist of fronds or blades detached from the substrate in various stages of degradation. However, we collected mature kelp blades from kelp fronds attached to the substrate that were

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free from epiphytes, to standardize the degradation state of the blades. We replicated each urchin density treatment four times for purple urchins and three times for red urchins. Prior to initiating a trial, we fed urchins *ad libitum* for at least 8 days. We then randomly assigned density treatments to foraging arenas and starved the urchins for 5 days, long enough to ensure gut passage while avoiding acute effects of starvation (Guillou et al. 2000). To initiate a grazing trial, we added 250 g of kelp to each arena, an amount which in preliminary trials allowed ample forage even at the highest urchin densities. We spun kelp blades for five seconds in a salad spinner to remove water on the surface of the blades and divided kelp into 25 pieces to standardize measures and blade size. We allowed purple urchins to graze for 48 hours and red urchins to forage for 96 hours because in preliminary trials red urchins exhibited comparatively slower foraging rates. At the end of each trial, we measured the amount of kelp consumed by spinning and weighing the remaining kelp following the same procedure (data available from SBC LTER et al. 2021a)

Per-capita consumption is well known to increase with consumer size (Rall et al. 2012). It is possible that the effect of biomass on consumption rate was confounded by the random size of urchins allocated into a trial, particularly in trials with low urchin density. To determine how body size impacted consumption rates, we conducted foraging trials in which we manipulated urchin size class at constant densities. However, analysis of the size data suggested that the trials in which we manipulated density by sampling different sized urchins were largely unaffected by random variation in body size (*see Appendix S1 for full discussion*). Therefore, for simplicity we focused on the relationship between consumer biomass (g m^{-2}) and foraging rate, making the explicit assumption that foraging rate is constant per unit mass of consumer (e.g. a small urchin and a large urchin consume the same amount per unit body mass).

In control trials without urchins, we found that kelp degradation over 96 hours was minimal relative to the accuracy of estimating the weight of kelp ($\sim \pm 2\%$ error). There was evidence of urchin mortality in 5 of the 50 grazing trials, with an average mortality of $<1\%$ of the trial population. One trial experienced 15% mortality, but exclusion of this trial from future analyses did not qualitatively change results.

The objective of the laboratory feeding experiments was to test between three alternative hypotheses for the relationship between grazing rate and biomass. The consumption rate of a population of urchin may increase in proportion to biomass, resulting in a linear relationship between consumption and biomass (*H1*). However, if urchins interfere with one another at high biomass, then increases in urchin biomass should result in total consumption rates increasing at a decelerating rate (*H2*). Alternatively, if increases in urchin biomass heighten the probability that any one urchin passively encounters kelp detritus, thereby allowing its neighbors to benefit, then total consumption rate will increase at an accelerating rate (*H3*).

To distinguish between these alternative hypotheses, we compared the fit of three different models to the mesocosm foraging data. A linear relationship between urchin biomass and consumption rate would support *H1*. If consumption increased at a decelerating rate (*H2*), then the data should follow a power-law function with an exponent < 1 . Alternatively, if consumption increased at an increasing rate (*H3*), then the data should follow a power-law function with an exponent > 1 . However, urchins may not facilitate conspecific foraging across all biomasses. Therefore, we also fit a phenomenological formulation of a sigmoid curve that allowed accelerating then decelerating grazing rates across certain ranges of density.

Specifically, we fit

$$G_i = \frac{aB_i^2}{b^2 + B_i^2} \quad (\text{Eq. 1})$$

where G_i is the observed consumption rate ($g_k \text{ m}^{-2} \text{ d}^{-1}$), B_i is the biomass ($g_u \text{ m}^{-2}$) of urchins in trial i , a represents the grazing rate at asymptotic biomasses ($g_u \text{ m}^{-2} \text{ d}^{-1}$) and b is the urchin biomass ($g_u \text{ m}^{-2}$) at the half-maximum of the function (Bolker et al. 2008), where k and u refer to kelp and urchin respectively. For the linear model, we fixed the y-intercept at zero because there cannot be consumption without consumers. We compared the fit of each model (linear, power-law, and sigmoidal) using Akaike's Information Criterion (AIC; Akaike 1973, Aho et al. 2014).

Observational data: How might historical foraging rates have varied across space and through time?

Our second objective was to hindcast urchin foraging rates using historical data on urchin biomass and our experimental estimate of the relationship between urchin biomass and foraging rate. The SBC LTER has conducted annual community surveys at nine sites in the Santa Barbara Channel since 2000. Specifically, researchers monitor the frond density of giant kelp along 40x2 m transects, which is converted to biomass based on established regression relationships (SBC LTER et al. 2021b) The SBC LTER also estimates the biomass of purple and red urchins, by averaging the number and test diameter of individuals encountered in six fixed quadrats (1 m^2) positioned along each transect. We applied our experimentally-derived relationship between foraging rate and urchin biomass to this time series of red and purple urchin biomass to estimate how much kelp could have been consumed by each species. We refer to these estimates as the predicted *consumptive capacity* (*sensu* Stevenson et al. 2016) of urchin populations to distinguish them from actual *in situ* measures of kelp consumption which were not measured.

Modeling: To what extent does detritus mediate consumer-driven disturbances to kelp?

Our final objective was to test the hypothesis that declines in standing kelp biomass occur when urchin foraging exceeds detrital production (e.g. Harrold and Reed 1985). To test this hypothesis, we combined predicted consumptive capacity with estimates of detrital supply calculated from monthly observations of kelp biomass dynamics collected by the SBC LTER at three of the nine sites (SBC LTER et al. 2021c). This time series includes monthly estimates of the proportion of biomass lost as fronds and blades from attached plants growing in fixed plots. We used these data to calculate the average proportion of the standing biomass of kelp lost as blades and fronds per day in summer from 2002-2020 at three sites. We multiplied the sum of these two loss rates by the summer standing biomass of giant kelp at each of transects where urchin biomass was measured to determine detrital supply at each of the transects at all nine sites. We found no evidence that the proportion of biomass lost as fronds and blades varied with standing kelp biomass or temperature (Appendix S2: Fig. S1). In California, the number of blades growing at different depths is approximately the same (Clendenning 1963) suggesting that the total fraction of biomass lost should not change with depth. In our calculation of detrital supply, we assume that all biomass lost is immediately available as detritus on the seafloor. In reality, some proportion of detrital biomass will be exported. Therefore, our estimate likely represents maximum detrital supply, and is conservative as detrital supply is likely lower than our estimate (*see Appendix S2 for more details on methodology*).

We used a generalized linear mixed effects model to test if the relationship between standing kelp biomass and urchin biomass was contingent on whether grazing rates exceeded detrital supply. We treated kelp biomass as the response variable and included two predictor variables as fixed effects: (1) urchin biomass– a continuous predictor, and (2) a categorical covariate encoding when consumptive capacity exceeded detrital supply (i.e. grazing > detritus).

We included site and year as random intercept effects to account for the structure of the data. We assumed that sites were spatially independent, since the distance between them is greater than the scale of spatial synchrony in kelp biomass dynamics (Cavanaugh et al. 2013). In our model, a significant interaction between urchin biomass and the grazing covariate would suggest that the effects of urchins on kelp depends on whether detrital biomass exceeded consumptive capacity. A main effect of urchin biomass or the overgrazing covariate would suggest that these factors operate independently (i.e. either the biomass of urchins is what matters alone, or the amount of grazing relative to detrital biomass matters alone). Considering biomass cannot be negative, we used a gamma distribution with log-link and added one to all kelp biomass estimates to account for zeros which cannot be modeled with a gamma distribution.

The model described above focuses on the instantaneous relationship between urchin biomass and kelp biomass at a given site-time combination. However, community processes (e.g. detrital supply, consumption rate) are dynamic and may more accurately describe changes in kelp biomass between time points versus instantaneous measures of biomass. Therefore, we also modeled the annual change in kelp biomass at each site (s) in year (t) ($\Delta K = K_{s,t} - K_{s,t-1}$) as a function of the rate of detrital supply relative to consumptive capacity. Specifically, we estimated the proportional difference between grazing (G) and detrital supply (D), as $\frac{G_{s,t} - D_{s,t}}{G_{s,t} + D_{s,t}}$. We used a linear mixed effects model that included random effects of site and year to predict the annual change in kelp as a function of the proportional difference between grazing and detrital supply.

We conducted all analyses in R version 4.0.4 (R Core Team 2021). We considered a parameter to be significant at $\alpha < 0.05$. For all models, we assessed if the residuals conformed to the assumed error distribution and tested for heteroscedasticity by comparing residuals and predictor variables (Harrison et al. 2018). When there was evidence for heteroscedasticity we

log-transformed predictor variables. In mixed effects models, we estimated confidence intervals conditional on fixed effects and estimated p -values via the Satterthwaite's degrees of freedom method using the lmerTest package and confirmed significance using likelihood ratio tests (Kuznetsova et al. 2017, Zuur et al. 2009).

RESULTS

Over the last 21 years, urchin biomass in the Santa Barbara Channel displayed considerable variation in time and space. Our experiments showed that grazing increased linearly with consumer biomass for both purple and red urchins. When applying the biomass-grazing relationships developed from the mesocosm experiment to hindcast grazing rates at SBC LTER study sites, we found that— like urchin biomass— historical kelp consumption likely varied considerably. Moreover, by merging our estimates of grazing with predictions of detrital kelp supply, our study offers new insights into when and where we expect urchins to deforest kelp and produce barrens.

Urchin biomass varied by species across nine kelp forest sites from 2000-2020 (Fig. 1). At a given transect, purple urchin biomass tended to be greater on average than red urchin biomass (*purple*: $200.3 \pm 0.4 \text{ g m}^{-2}$, *red*: $114.5 \pm 0.3 \text{ g m}^{-2}$; ANOVA: $F_{1,1534} = 38.8$, $p < 0.001$; Fig. 1a), largely due to their 10-fold higher average density (*purple*: $9.4 \pm 0.02 \text{ ind. m}^{-2}$, *red*: $0.9 \pm 0.002 \text{ ind. m}^{-2}$; ANOVA: $F_{1,1534} = 203.3$, $p < 0.001$). Urchin biomass has generally declined since 2000, with a peak between 2009 and 2014, though there is evidence for a recent increase at some sites (Fig. 1b).

The total biomass of kelp consumed by urchins (i.e., consumptive capacity) in mesocosm experiments increased linearly with urchin biomass for both purple and red urchins (Fig. 2;

purple: $\beta = 0.02 \pm 0.002$, $p < 0.001$, $R^2 = 0.82$; *red*: $\beta = 0.0091 \pm 0.002$, $p < 0.001$, $r^2 = 0.59$). We found no evidence for a nonlinear relationship between urchin biomass and consumptive capacity. AIC-comparison suggested nearly equivalent fits of linear, power-law, and sigmoid relationships for both species ($\Delta AIC < 2.5$, Appendix S3: Table S1, S2). However, there was no evidence of a positive or negative slope in the relationship between per-capita consumption rate and urchin biomass (Appendix S3: Fig S1; *purple*: $p = 0.43$, $R^2 = 0.04$; *red*: $p = 0.14$, $R^2 = 0.07$), suggesting that a linear relationship is the most parsimonious explanation of how population-scale foraging rates change with urchin biomass. Considering the experimental evidence that foraging rates increase linearly with urchin biomass, consumptive capacity varied in direct proportion with urchin biomass (Fig. 3). There was more variation in consumptive capacity across space than through time ($CV_{\text{time}} = 1.29 \pm 0.34$, $CV_{\text{space}} = 1.96 \pm 1.72$).

Across 21 years of data at nine sites, urchin biomass was negatively correlated with kelp biomass, but explained only 14% of the variation in kelp dynamics (Appendix S4: Table S1). At many sites or years kelp biomass remained high, despite urchin biomass far exceeding thresholds expected to drive transitions toward urchin-dominated deforested states either locally in southern California (e.g. 1246 g m^{-2} ; Dean et al. 1984) or elsewhere in the world (e.g. $\gg 668 \text{ g m}^{-2}$; Ling et al. 2015). By accounting for instances when detrital supply exceeded consumptive capacity, our best fit model explained $\sim 70\%$ of the variation in foraging rates ($\Delta AIC = 461.0$, Appendix S4: Table S1), supporting the hypothesis that urchin-driven declines in kelp are mediated by the availability of detritus in the Santa Barbara Channel (Fig. 4). In fact, when the rate of detrital supply was greater than consumptive capacity, kelp biomass increased with increases in urchin biomass (Fig. 4a). When consumptive capacity exceeded detrital supply, kelp biomass was on average $\sim 50x$ less than when consumptive capacity was less than detrital supply (Fig. 4b).

The availability of detritus relative to consumptive capacity also predicted variation in annual kelp dynamics. On average, the annual change in standing kelp biomass switched from positive to negative as the consumptive capacity increased relative to detrital supply (Fig. 5; LMM: $\beta = -1486.8 \pm 288$, $p < 0.001$, Appendix S4: Table S2). When consumptive capacity was greater than detrital supply (e.g. right hand side of Fig. 5), kelp declined or changed little (e.g. did not increase by more than $+100 \text{ g m}^{-2}$), 91% of the time, compared to only 42% of the time when detrital supply exceeded consumptive capacity. Generally, changes in kelp biomass were dissociated from grazing dynamics when consumption was less than detrital supply (e.g. left side Fig. 5), and even when urchin biomass was high, kelp biomass increased 15% of the time.

DISCUSSION

Ultimately, the productivity of a community is dynamic, driven by the complex interplay between the rates that primary producers grow and are consumed. Yet empirical determination of what controls productivity over space and time is often hampered by the availability of long-term data. Here, we combine mesocosm experiments with 21 years of spatially explicit data on rocky reef community structure to demonstrate how the balance between two dynamic processes—consumption and primary production—mediate consumer-driven disturbances in the key foundation species, *Macrosystis pyrifera*, of California kelp forests.

Consumer-resource theory predicts that the rate that primary producers are consumed is dependent on resource density, consumer density, and body size (Abrams and Ginzburg 2000, Rall et al. 2012). In our mesocosm trials we quantified how foraging rates varied as a function of consumer biomass by manipulating consumer density and sampling individuals from the size distribution observed in local populations. Previous work on various urchin species, along with

evidence from our own size-based foraging trials, suggests that total biomass, rather than size-specific consumption rates, is an appropriate predictor of an urchin population's consumptive capacity (Stenvenson et al. 2016, Suskiewicz and Johnson 2017, Appendix S2). We found that for both purple and red urchins, consumption of kelp blades increased linearly with consumer biomass, suggesting that even at high consumer biomass grazing rates do not decelerate due to competition or accelerate due to facilitation.

Our finding that urchins continue to eat in direct proportion to their biomass even at high densities, offers critical insight into the mechanisms triggering consumer-driven disturbances in Southern California kelp forests. By estimating the consumptive capacity of historical urchin populations as a linear function of urchin biomass, we showed that kelp dynamics were independent of urchin biomass when the rate that detritus was produced exceeded the consumptive capacity of urchins. However, when consumptive capacity exceeded detrital supply, the biomass of standing kelp was 50-fold less, supporting the long-standing hypothesis that the persistence of kelp forests is driven by the rate of detrital consumption relative to detrital supply (e.g. Harrold and Reed 1985). Therefore, our work suggests that when detrital resources become limiting, kelp forests are likely to shrink or disappear, and may be transformed into urchin-dominated deforested communities with lower primary productivity. Furthermore, recent work demonstrated that urchins rapidly consume algal recruits in barren areas leading to the bioerosion of long-lived calcareous reefs (Rasher et al. 2020), reinforcing alternative ecosystem states (Konar and Estes 2003). Therefore, the capacity of urchins to continue to graze in proportion to their biomass suggests that when food becomes scarce urchins may prevent kelp regrowth and perpetuate consumer-dominated communities.

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To date, efforts to predict when kelp forests will transition to urchin-dominated states have primarily focused on ecological indicators of grazing pressure such as urchin density (Filbee-Dexter and Scheibling 2014, Ling et al. 2015), or on factors— such as predators— that alter urchin abundance (Estes et al. 2010, Hamilton and Caselle 2015, Dunn and Hovel 2019). However, our study highlights the importance of focusing on the rates of community processes (detrital production and herbivory) in addition to the state variables such as the density or size of consumers and resources. In our study system, quantifying urchin biomass alone was not sufficient to accurately predict when a kelp community was at risk of deforestation. We observed numerous instances where kelp biomass remained high despite the presence of dense urchin populations. Instead, we found that reductions of intact kelp biomass were highest when grazing outweighed detrital supply rates. In fact, when detrital supply was higher than consumptive capacity, kelp and urchin biomass positively covaried, likely due to similar habitat requirements or because urchin population growth rates are positive when detrital resources are plentiful. The role of detrital supply in triggering a switch in urchin foraging mode (and subsequent loss in intact kelp biomass) is supported by empirical evidence that shows urchins in kelp-dominated sites consume more detritus than standing kelp, compared to urchins in urchin-dominated sites which consume both detritus and standing kelp at similar rates (Kriegisch et al. 2019).

Estimation of detrital production and consumptive capacity could offer scientists and resource managers the opportunity to identify kelp forests at risk of deforestation. Resulting “risk maps” may be particularly useful for optimizing conservation and management funds (e.g. Avila et al. 2018). For example, sites where urchin populations have a high consumptive capacity relative to detrital production are likely places for targeted urchin harvest before the community transitions into an urchin-dominated state. However, the factors driving deforestation by urchins

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may vary between different kelp ecosystems (Filbee-Dexter and Scheibling 2014, Karatayev et al. 2021). To effectively predict risk of deforestation in diverse kelp communities requires regionally-specific research on the role of detritus and the causes of variation in detrital supply. For instance, in Southern California kelp forests, detrital dynamics exhibit a pronounced seasonal signal (Yorke et al. 2019) caused by seasonal storms and blade senescence patterns (Rodriguez et al. 2013). Yet empirical estimates of the rates of detrital turnover, import, and export remain unclear. Furthermore, temperature is well known to alter consumption rates (Uiterwall and DeLong 2020, Brown et al. 2004). While we focused only on consumption rates during the boreal summer, accounting for temperature specific grazing rates is likely a key component of mapping the risk of deforestation, particularly in future projections when increasing ocean temperature will likely increase consumption rates to a thermal optimum.

The prevalence of disturbances driven by primary consumers will likely increase with global climate change and associated losses of higher predatory species (Rocca et al. 2021, Silliman et al. 2013). Therefore, it is critical to understand the mechanisms by which consumers switch from coexisting with primary producers to overgrazing the dominant producer, resulting in an alternative community state. Our study highlights the importance that detrital resources play in mediating consumer-driven disturbances on temperate rocky reefs in southern California by demonstrating that a behavioral switch from passively feeding on kelp detritus to actively grazing on standing kelp can trigger deforestation. The importance of detrital supply in consumer-resource dynamics is not exclusive to kelp forests. For example, there is evidence that the widespread degradation of saltmarshes on the US eastern seaboard is linked to a change in the dominant consumer, *Littoraria irrorata*, foraging on the detritus of marsh grass to actively foraging standing biomass (Silliman et al. 2005). Recent work shows that the majority of primary

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consumers forage on both detrital resources and living biomass (Wolkovich et al. 2014), suggesting that declines in detrital availability, such as the switch from detritivory to herbivory by urchins in California kelp forests, could underlie consumer-driven disturbances that result in dramatic ecosystem change in other systems.

Understanding sources of variation in foraging rates is foundational to answering the long-debated question in ecology, ‘why is the world green?’ (Hairston et al 1960, Murdoch 1966). The answer to this question inevitably lies in the balance between the rates at which plant matter is produced and consumed. Our research offers a case study in answering this question. We show how the consumptive capacity of urchin populations shifts in response to changes in urchin biomass and highlight how the persistence of giant kelp depends on the balance between foraging pressure and detrital production, with implications for anticipating and reversing shifts in community state.

ACKNOWLEDGMENTS

We thank Dr. Holly Moeller for thoughtful discussions on the development of this manuscript, numerous undergraduate researchers who cared for the sea urchins used in this study, and C. Nelson, S. Sampson, S. Harrer, and the rest of the SBC LTER research and data management team for their commitment to collecting long-term ecological data. This work was funded by an NSF Graduate Research Fellowship (BD), the California Sea Grant Prop 84 grant program (R/OPCOAH-2), and the Santa Barbara Coastal Long-Term Ecological Research program (NSF OCE 1831937).

AUTHOR CONTRIBUTIONS

M.R. and B.P.D. contributed equally to this manuscript. B.P.D. and A.C.S. conceived the idea. M.R., B.P.D. and J.C. collected grazing data. D.C.R designed and collected the time series data. B.P.D and M.R. conducted analyses. M.R., B.P.D., and A.C.S. wrote the paper, and J.C. and D.C.R contributed substantial comments and revisions on drafts.

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FIGURE CAPTIONS

Figure 1. (a) Variation in biomass for purple (*Strongylocentrotus purpuratus*) and red (*Mesocentrotus franciscanus*) sea urchins across 21 years in the Santa Barbara Channel. (b) Total urchin biomass varied between sites and across years. Colored lines represent combined urchin biomass for nine sites averaged across transects. Black line represents the average biomass across all sites.

Figure 2. Experimental consumption rate of kelp blades by purple (a) and red (b) urchins in mesocosm foraging trials. The gray polygons represent the range of biomass that previous research has identified as possible thresholds leading to urchin-dominated community states (e.g. urchin barrens). The lower end of the range is the global average across temperate kelp forest communities (Ling et al. 2015), while the upper range is the threshold biomass for California kelp forests (Dean et al. 1984).

Figure 3. Spatial and temporal variation in the consumptive capacity of urchin populations at nine sites in the Santa Barbara Channel. Consumptive capacity was calculated based on 21-years of urchin biomass observations and the experimental relationship between urchin biomass and foraging rate (*see methods for details*). Gray shading surrounding points represents the SE of the mean across years. Each site is accompanied by a time series of normalized kelp (*Macrocystis pyrifera*) and combined sea urchin biomass (g m^{-2}). One site was omitted for visualization purposes only. Bathymetric data from Divins and Metzger (2021).

Figure 4. Relationship between standing kelp biomass (e.g. kelp attached to the substrate) and total urchin biomass across 21 years at sites in the Santa Barbara Channel. (a) Standing kelp biomass was best explained by an interaction between urchin biomass and whether the consumptive capacity of urchins was greater or less than the estimated detrital supply rate. Lines

in (a) represent the average prediction (\pm 95% CI) for the relationship between urchin and kelp biomass when consumption exceeded, or was less than, detrital supply from a generalized linear mixed effects model. (b) When consumptive capacity exceeded the detrital supply rate, standing kelp biomass was on average \sim 50x less than when detrital supply exceeded the consumption rate.

Figure 5. Relationship between the annual change in kelp biomass and the proportional difference between detrital supply ($\text{g m}^{-2} \text{d}^{-1}$) and consumptive capacity of urchin populations ($\text{g m}^{-2} \text{d}^{-1}$) (*see Methods for details*). When the rate of detrital supply exceeds consumption (left), kelp biomass dynamics were decoupled from urchin consumption. As the consumption rate increased relative to detrital supply, the annual change in kelp biomass declined ($\beta = -1486.8 \pm 288$, $p < 0.001$). Line represents the average prediction (\pm 95% CI) from a linear mixed effects model. The horizontal line at zero represents no change in kelp biomass from year to year, while the vertical line at zero represents when consumptive capacity was equal to the rate of detrital supply.

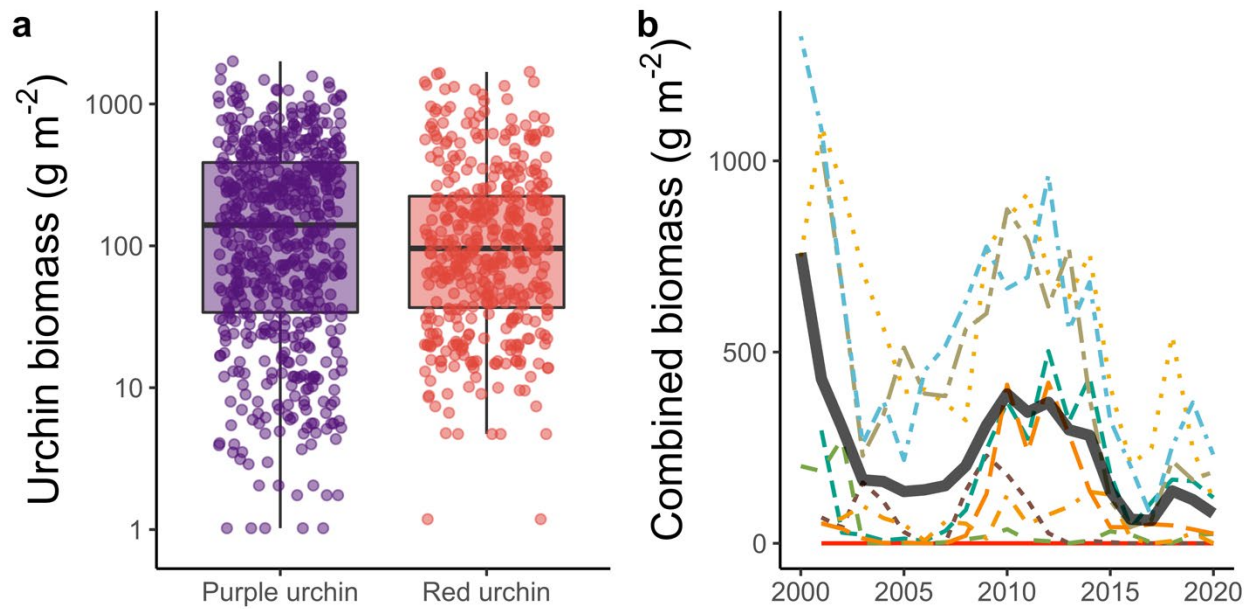


Figure 1.

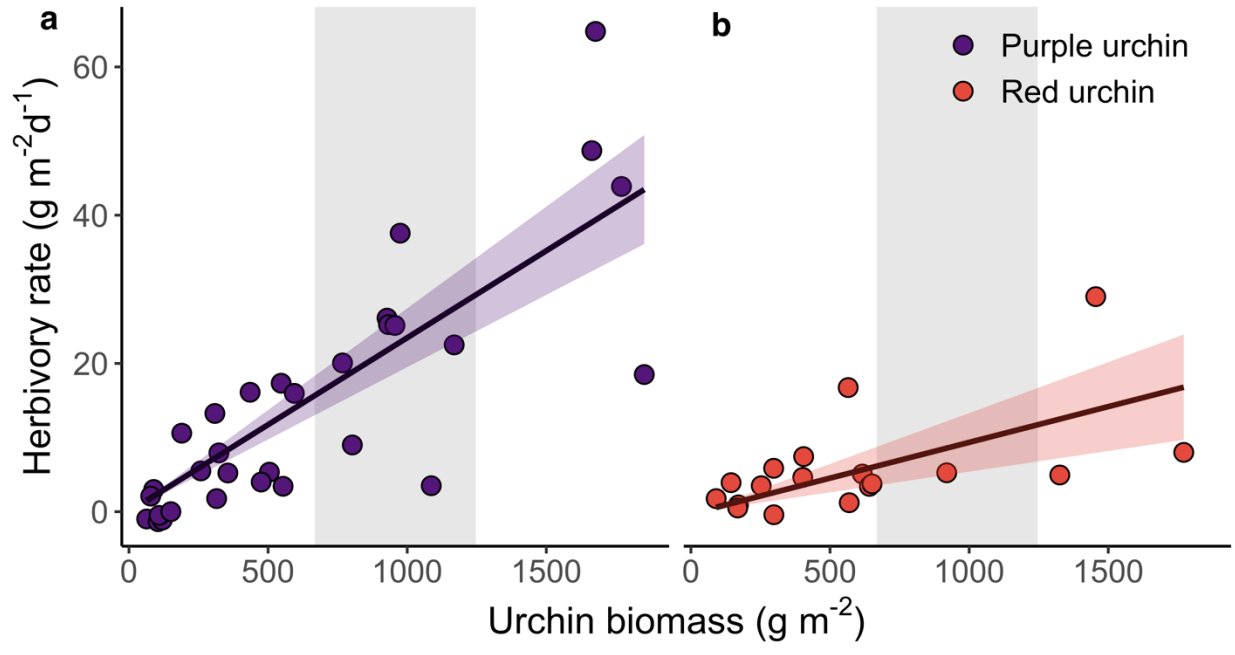


Figure 2.

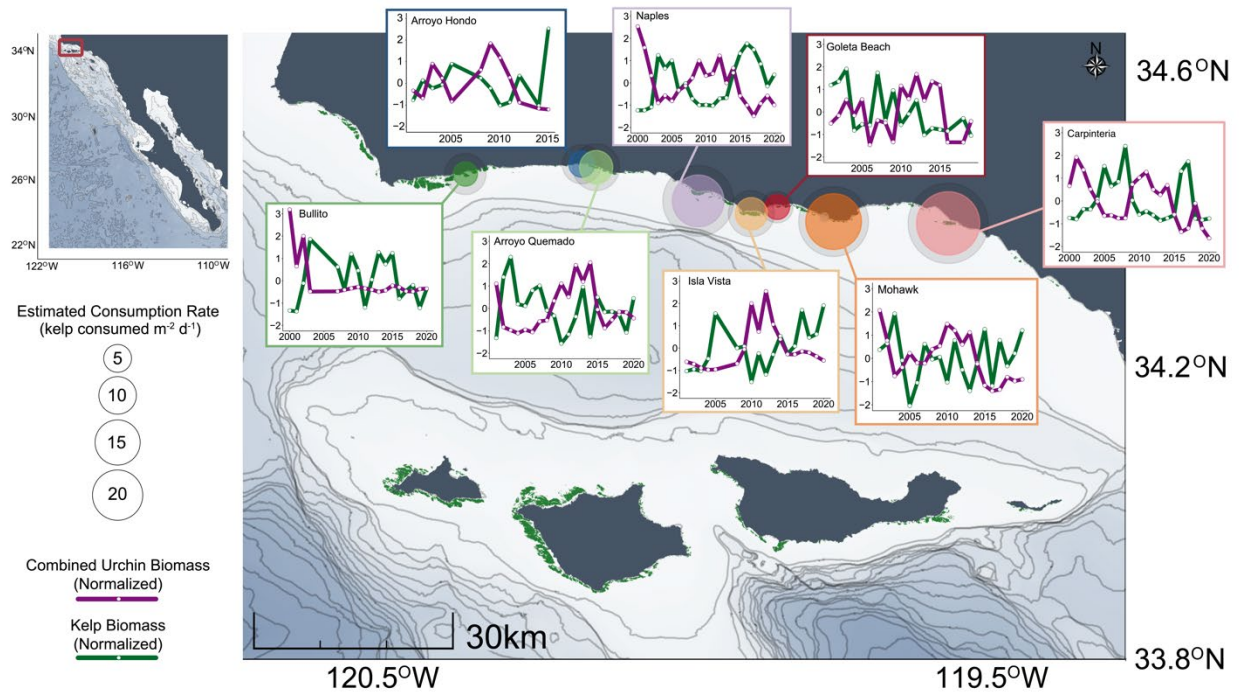


Figure 3.

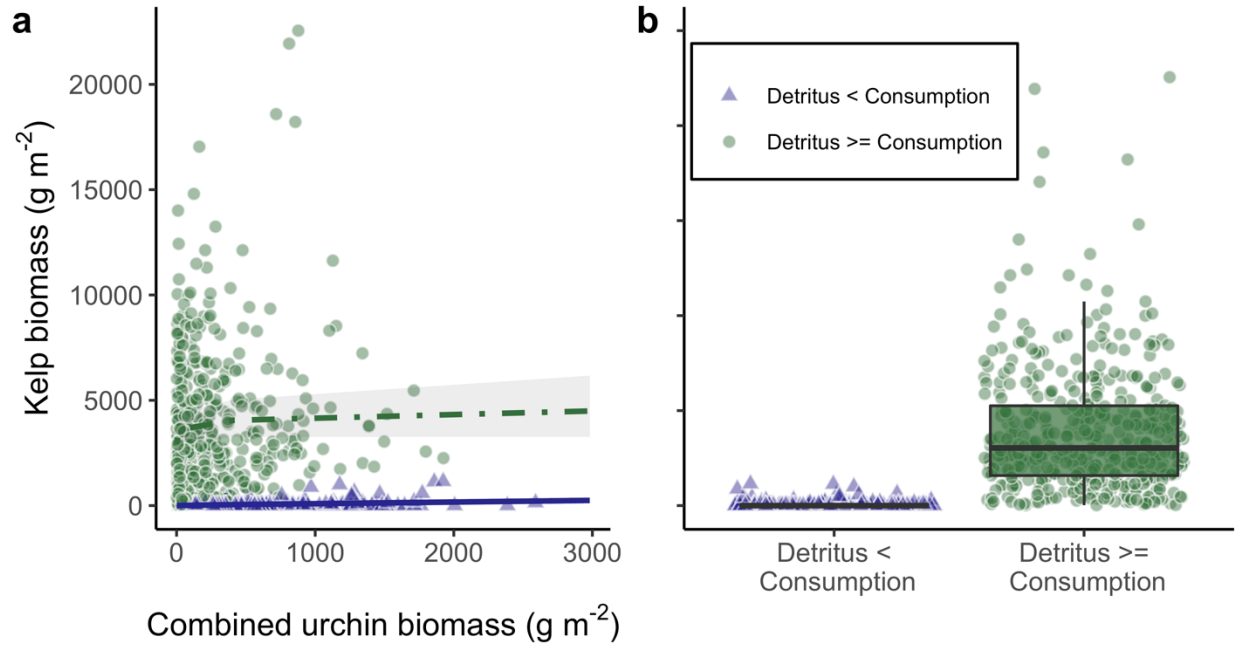


Figure 4.

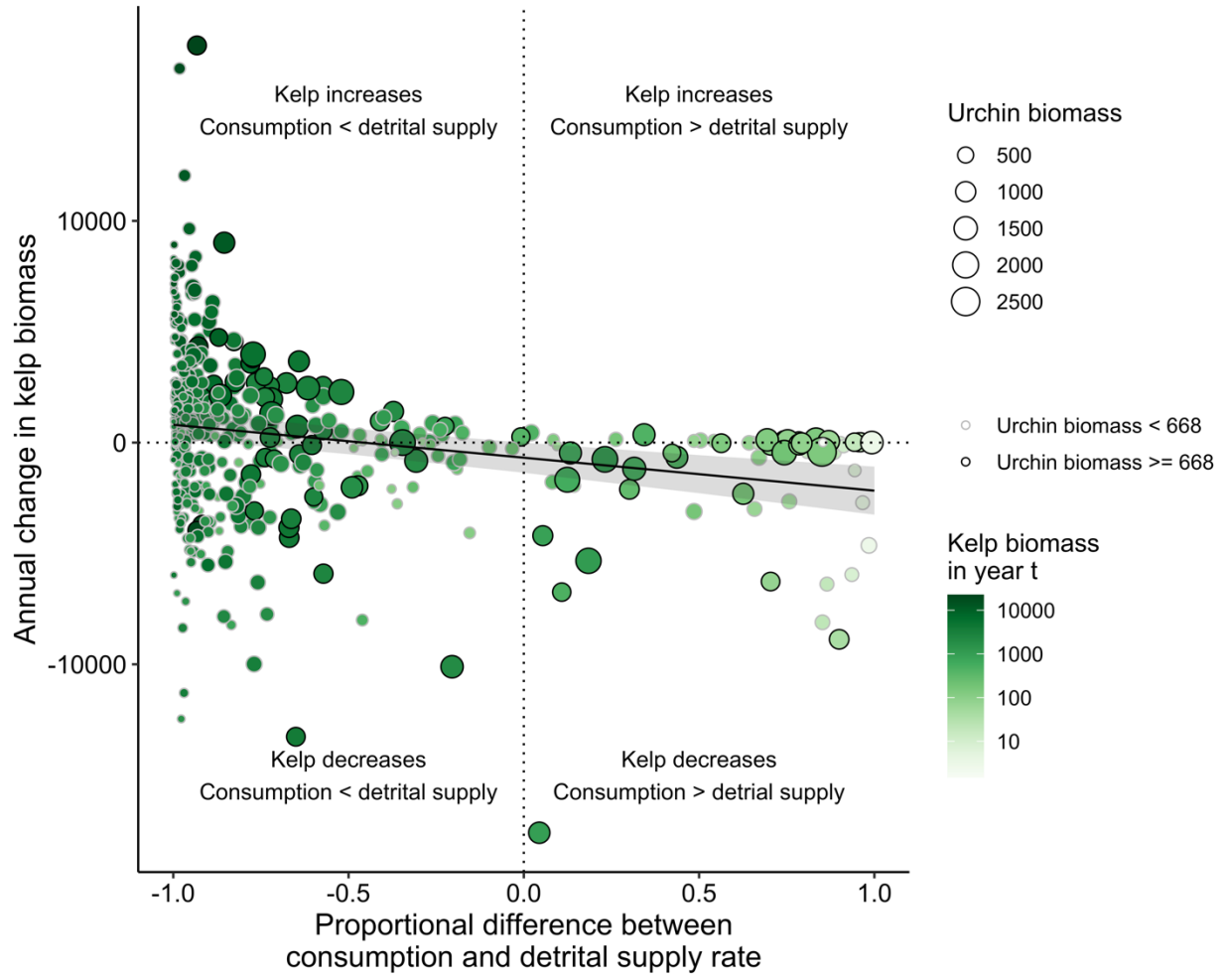


Figure 5.