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Long-term patterns of benthic irradiance and kelp production in the central Beaufort sea reveal implications of warming for Arctic inner shelves

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ABSTRACT

This study synthesizes a multidecadal dataset of annual growth of the Arctic endemic kelp *Laminaria solidungula* and corresponding measurements of *in situ* benthic irradiance from Stefansson Sound in the central Beaufort Sea. We incorporate long-term data on sea ice concentration (National Sea Ice Data Center) and wind (National Weather Service) to assess how ice extent and summer wind dynamics affect the benthic light environment and annual kelp production. We find evidence of significant changes in sea ice extent in Stefansson Sound, with an extension of the ice-free season by approximately 17 days since 1979. Although kelp elongation at 5–7 m depths varies significantly among sites and years (3.8–49.8 cm yr^{-1}), there is no evidence for increased production with either earlier ice break-up or a longer summer ice-free period. This is explained by very low light transmittance to the benthos during the summer season (mean daily percent surface irradiance ± SD: 1.7 ± 3.6 to 4.5 ± 6.6, depending on depth, with light attenuation values ranging from 0.5 to 0.8 m^{-1}), resulting in minimal potential for kelp production on most days. Additionally, on month-long timescales (35 days) in the ice-free summer, benthic light levels are negatively related to wind speed. The frequent, wind-driven resuspension of sediments following ice break-up significantly reduce light to the seabed, effectively nullifying the benefits of an increased ice-free season on annual kelp growth. Instead, benthic light and primary production may depend substantially on the 1–3 week period surrounding ice break-up when intermediate sea ice concentrations reduce wind-driven sediment resuspension. These results suggest that both benthic and water column primary production along the inner shelf of Arctic marginal seas may decrease, not increase, with reductions in sea ice extent.

1. Introduction

Seasonal sea ice cover plays a prominent role in marine primary productivity in high-latitude ecosystems, as it can set the timing of peak production and determine annual light budgets (Kahru et al., 2011; Clark et al., 2013; Ji et al., 2013; Post et al., 2013). In the Arctic Ocean, there has been a striking decline in sea ice extent since the onset of observations via satellite measurements, at a rate of approximately 13.3% loss in area per decade (Serreze and Stroeve, 2015). Despite ongoing efforts by scientists to investigate the effects of sea ice loss on pelagic production (reviewed in Wassmann and Reigstad, 2011), only a few studies to date have addressed the direct consequences on benthic production (Krause-Jensen et al., 2012; Clark et al., 2013; Krause-Jensen and Duarte, 2014). In coastal Arctic systems, benthic primary production by macro- and micro-algae in Arctic waters is important to ecosystem production, elemental cycling, and food web dynamics, especially during times of limited pelagic production (Dunton and Schell, 1987; Glud et al., 2009; McMeans et al., 2015; Renaud et al., 2015). Additionally, bio-physical processes in shallow, nearshore Arctic areas, where much of this production takes place, remain understudied due to logistical constraints (e.g. Fritz et al., 2017). Changes to production in these areas would have broad consequences for Arctic ecosystem function.

Because of the strong annual cycle of solar irradiance in polar regions, seasonal sea ice and solar energy models predict that earlier dates of ice break-up will result in exponential increases in benthic light budgets (Clark et al., 2013). For instance, Krause-Jensen et al. (2012) and Clark et al. (2013) used existing gradients in seasonal ice cover in Greenland and Antarctica, respectively, to link lengthened ice-free seasons with increases in macroalgal production and hypothesized that future warming-driven reductions in seasonal sea ice extent and duration will enhance annual production by benthic macrophytes. These predictions contribute to the idea that Arctic coastal habitats will become increasingly macrophyte-dominated as Arctic warming continues, with consequences for Arctic food webs and seawater chemistry (Clark et al., 2013; Krause-Jensen and Duarte, 2014; Krause-Jensen et al.,

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2016). However, variations in underwater optical properties, which have a profound influence on light transmittance to the benthos and demonstrable impacts on benthic primary production (Van Duin et al., 2001), are largely overlooked in these analyses. Bartsch et al. (2016) hypothesized that enhanced sediment inputs from glacial melt caused a narrower euphotic zone during the open-water season, leading to observed shallowing of peak biomass and shallower depth limit of kelps in Svalbard over the past two decades. The links between ice loss, irradiance at depth, and primary production appear to be multifaceted and warrant further investigation.

While ice cover determines irradiance at the water's surface, irradiance at depth depends on light attenuation in the water column. In the coastal Arctic Ocean, summer water transparency is influenced by concentrations of phytoplankton and sediments suspended in the water column. Concentrations of suspended sediments during the open-water summer in the coastal Beaufort Sea have been directly linked to increased light attenuation and decreased annual production by benthic macroalgae (Aumack et al., 2007). Many Arctic inner shelf areas (depth < 10 m), such as the Alaskan Beaufort Sea coast, have particularly high suspended sediment concentrations due to shallow depth, persistence of unconsolidated sediments, and significant inputs by numerous rivers and streams (notably, the Arctic Ocean receives 11% of global river discharge, but only constitutes 1% of global ocean volume; McClelland et al., 2011). These sediments originate from coastal erosion, resuspension due to water motion, and fluvial inputs by Arctic rivers, which discharge the large majority of their annual suspended sediment loads by the end of the spring melt (Wegner et al., 2003; O'Brien et al., 2006; Walker et al., 2008). Because most river fluxes occur before the end of ice break-up, changes in wind direction and/or speed during the open-water period are the main drivers of temporal variability in underwater irradiance in the nearshore areas, as they are in other shallow aquatic systems (Van Duin et al., 2001). Annual benthic light budgets may consequently have a negative relationship with wind speeds during the ice-free season.

The primary objective of this paper is to examine how sea ice extent and wind dynamics affect variation in the annual benthic light budget and production by the Arctic endemic kelp *Laminaria solidungula* in the central Beaufort Sea. Since 1979, sea ice duration in the Beaufort Sea has decreased at an accelerating rate, while summertime easterly winds have increased in speed and frequency across the coastal region (Wood et al., 2013, 2015; Frey et al., 2015). These long-term environmental changes may have significant, but opposing, effects on long-term primary production patterns. Although lengthened ice-free season results in increased irradiance at the waters' surface, enhanced summer winds may degrade the underwater light climate. Frond elongation in *L. solidungula*, is entirely dependent on the utilization of photosynthetically derived carbon reserves produced the previous summer (Dunton and Schell, 1986). The resulting annual growth has a strong correlation with the light budget of the preceding ice-free season (Dunton, 1990). This species is ideal for assessing the biological effects of changes to the Arctic underwater light environment due to its enhanced capacity to respond to small changes in irradiance compared to other kelp species, particularly evident in its low saturating irradiance for photosynthesis (38 μmol photons sec^{-1}; Dunton and Jodwalis, 1988).

Multidecadal time series that document biological responses to variations in regional climate in Arctic marine systems are rare, but critical for the development of accurate projections of future ecosystem change (Wassmann et al., 2011). Here, we synthesize a multidecadal dataset (collected between 1977 and 1992, and 2002 through 2008) and incorporate previously unpublished data (2012 through 2016), on benthic irradiance and kelp growth from Stefansson Sound in the central Beaufort Sea (Dunton, 1990; Dunton et al., 1992, 2009; Aumack et al., 2007) to demonstrate the combined influence of seasonal ice extent and wind dynamics on the annual light budget, and annual kelp production. Additionally, we assess whether annual variations in *L. solidungula* growth relate to seasonal ice extent and summer wind dynamics. In doing so, this work highlights the importance of including factors that affect underwater light transmittance in projecting changes in primary productivity and ecosystem structure in Arctic marine ecosystems.

2. Methods

2.1. Study site

The Stefansson Sound Boulder Patch (hereafter 'the Boulder Patch') is an isolated rocky zone of boulders and cobbles covering an area of approximately 63 km^2 in a region dominated by soft sediment (Barnes and Reimnitz, 1974; Fig. 1). Located in relatively shallow water (4–8 m) within 15 km of the coast, the Boulder Patch remains a non-depositional environment despite its proximity to the Sagavanirktok River, which has a 1–2 week period of peak discharge in late May and early June (Dunton et al., 1982; Rember and Trefry, 2004)

The epilithic community in the Boulder Patch is dominated by the kelp *L. solidungula* and represents a regional biodiversity hotspot. Research conducted in the area since the 1970s has focused primarily on characterizing the underwater light environment and the biological production of *L. solidungula* (Dunton, 1985; Dunton and Schell, 1986, 1987, Dunton et al., 1992, 2009; Henley and Dunton, 1995; Aumack et al., 2007). Field studies have been nearly continuous since 1978 except for a single seven-year lapse (1993–2000), with ten long-term study sites occupied since 1984 (Fig. 1).

2.2. Kelp production

Laminaria solidungula individuals from long-term study sites were collected by SCUBA divers at one- or two-year intervals. The thallus of this species consists of a single blade with multiple ovate growth sections, each representing one year of production. The blade section closest to the stipe represents production from the most recent year and the immediate distal section represents growth from the previous year. Because multiple years of production can be measured from a single individual, this dataset spans from 1976 to 1990 and 1996 to 2015.

2.3. Benthic and surface irradiance

Spherical quantum sensors (LI-193SA, LI-COR Inc.), placed ~0.5 m above the benthos, were deployed for measurements of photosynthetically active radiation (PAR) at sites across the Boulder Patch (Fig. 1, Supp. Table 1). Sensors were deployed in conjunction with either CR21 (Campbell Scientific), LI-1000, LI-1400, or LI-1500 dataloggers (LI-COR Inc.), depending on the site and study year (Supp. Table 1). Cosine PAR sensors (LI-192SA, LI-COR Inc.) deployed in line with a LI-1000 datalogger collected continuous surface light measurements at East Dock in Prudhoe Bay (1986–1987) and Endicott Island (1987–2016; Fig. 1). Sensors were cleaned between deployments (once a year), as bio-fouling in this environment is negligible. Sensors made instantaneous measurements every minute and logged the average every 1 or 3 h, depending on site and study year (Supp. Table 1). All PAR measurements were converted into total daily photon flux rate (mol m^{-2} day^{-1}) for analysis. Daily hours of saturating irradiance for *L. solidungula* (H_{sat}: hours with average photon flux rate ≥ 38 μmol photon m^{-2} sec^{-1}; Dunton and Jodwalis, 1988) were also calculated, as this metric is more closely related to annual production than photon flux rate (Dunton, 1990). For years with irradiance data for > 90% of the year, annual H_{sat} was calculated at each site.

2.4. Sea ice

Sea ice concentration from 1979 to 2016, measured via passive microwave data, was obtained from the National Sea Ice Data Center via the Arctic Data Integration Portal (http://portal.aoos.org) for the