Journal of Experimental Marine Biology and Ecology 574 (2024) 151984

Contents lists available at ScienceDirect

Journal of Experimental Marine Biology and Ecology

journal homepage: www.elsevier.com/locate/jembe

Short Communication

Comment: A reexamination of Johnston et al., 2023, bed-scale impact and recovery of a commercially important intertidal seaweed

Robin Hadlock Seeley [a,*], Sarah Hardy [b], Nancy K. Prentiss [b], Walter H. Adey [c]

[a] P.O. Box R, Pembroke, ME 04666, USA
[b] University of Maine at Farmington, Farmington, ME 04938, USA
[c] National Museum of Natural History (NMNH), Smithsonian Institution, PO Box 37012, Washington, DC 20013-7012, USA

ARTICLE INFO

Keywords:
Ascophyllum nodosum
Rockweed
Seaweed harvest
Brown algae
Intertidal
Gulf of Maine

ABSTRACT

Johnston et al., 2023 (Bed-scale impact and recovery of a commercially important intertidal seaweed. J. Exp. Mar. Biol. Ecol. 561) report that rockweed biomass recovers to pre-harvest levels one year after commercial harvest. The Johnston et al. study has two major problems in design, execution, and interpretation of results: 1) industry partner conflict of interest and statistically undetectable impact of the harvest treatment on *Ascophyllum nodosum* (rockweed) beds, 2) incomplete statistical analysis with inappropriate inferential conclusions about biomass recovery of harvested rockweed beds. Our analysis of their data shows that the only regions of the coast where rockweed biomass recovered to pre-harvest levels are the three regions where the harvest treatment was never detectable. In the one region where the harvest treatment was detectable, rockweed biomass did not recover to pre-harvest levels in a year. Rockweed is a foundational species in the rocky intertidal food web as well as an ecosystem engineer. The improper interpretation by Johnston, et al. of the study data is misleading ecosystem managers and the public about the impacts of commercial rockweed harvests. Most concerning, this paper sets a false foundation for marine policy on commercial rockweed harvesting in Maine.

1. Introduction

For >40 years, we have been studying the intertidal community of rockweed (*Ascophyllum nodosum* (Linnaeus) Le Jolis, 1863), the harvesting of this macroalga, and the impacts of rockweed harvests in Maine (Adey, 1982; Adey and Hayek, 2011; Adey et al., 2020; Seeley, 1986; Seeley and Schlesinger, 2012). One of us (WA) did an extensive two-year study of the *Ascophyllum*-dominated intertidal zone on rocky shores of Gouldsboro Bay (Adey et al., 2020) and found that the rockweed turnover time in undisturbed populations there with enough biomass to be commercially attractive for harvest is ~2.3 years. Vadas et al. (2004) found a similar rate for Cobscook Bay (~2.0 years). Three lines of evidence — our direct observations of the impact of commercial rockweed harvests, the data on turnover times in populations of undisturbed rockweed, and the studies that report it takes 2–3 years for rockweed biomass to return to a pre-harvest level — have led us to question the conclusion by Johnston et al., 2023 (going forward, Johnston et al.) that it takes just one year for the biomass of rockweed beds to recover from commercial harvest.

We present here evidence for challenging the conclusion of Johnston et al. that “recovery, especially in biomass, can occur within a single year at the bed-scale using current commercial methods.” We recognize that the Johnston et al. study was a large undertaking and appreciate what has been learned about state-wide rockweed population studies of this size from their work.

Fundamental problems in the study design of Johnston et al. cast doubt on the authors’ conclusions. The design was as follows: at 19 control sites, rockweed beds were not harvested; at 19 impact sites, rockweed beds received rockweed harvest treatment. Johnston et al. report that sampling was performed and data collected at three time points: pre-harvest, some unknown time after harvest, and one full year post harvest.

We found two major problems in design, execution, and interpretation of results: 1) industry partner conflict of interest and statistically undetectable impact of the harvest treatment on *Ascophyllum nodosum* (rockweed) beds, 2) incomplete statistical analysis with inappropriate inferential conclusions about biomass recovery of harvested rockweed beds.

---

* Corresponding author.
E-mail address: rhs4@cornell.edu (R.H. Seeley).

https://doi.org/10.1016/j.jembe.2023.151984
Received 20 June 2023; Received in revised form 1 November 2023; Accepted 18 December 2023

2. Problems in design, performance, analysis and conclusions of Johnston et al.

2.1. Undetectable impact of the experimental treatment on Ascophyllum nodosum (rockweed) bed biomass

An accurate and therefore meaningful study of rockweed bed "recovery" following a harvest requires verification of two premises: (1) the treatment, commercial harvest, was applied at the "impact" sites and (2) the treatment was not applied at the control sites. Unfortunately, neither (1) nor (2) is shown clearly in this study.

Instead, in 42% of the impact transects (16 of 38, Table 1, Johnston et al.) there was no decrease in biomass, and in three of four study regions there was no significant decrease in biomass after harvest (Johnston et al. Table S2). Johnston et al. recognized this, stating "Midcoast was the only region to experience statistically significant declines in rockweed height or biomass following harvest."

Why were treatment effects undetectable in 75% of the study regions and nearly half of the impact transects? This could be due to several factors, including 1) lack of overlap between a harvested area and the area subsequently sampled (acknowledged by Johnston et al.); 2) reported post-harvest sampling could have taken place before harvest; 3) conflict of interest in research partners required verification of harvest, harvest dates and harvest intensity, but verification was mostly lacking.

2.1.1. The area of rockweed bed sampled in the harvest year did not overlap the harvested areas at "impact" sites

Researchers may not have known the location of harvest within the site or the size of the harvested area. Moreover, sampling occurred only in the middle of the rockweed zone, while typical commercial rockweed harvesting occurs as well in the high and low rockweed zone (unpublished data). Johnston et al. acknowledge that they did not ensure that sampled areas and harvested areas overlapped. "We did not ensure that there was perfect spatial overlap between harvest and either our quadrats or our transects, and harvesters were unaware of the location of sampling within each site."

The Before-After-Control-Impact (BACI) design typically involves the study of an impact that occurs over an entire study area that has been adequately sampled. Johnston et al., however, sampled only two 10 m^2 transects out of 100 possible 10m^2 transects in the middle third of a single 3000 m^2 site. In short, the authors sampled 2% of the potential harvest area in the mid zone and 0% of the potential harvest area in the high zone or low zone. A BACI design is not well-suited to studies in which the impact varies by location *within* a site (Kerr et al., 2019). Studies unable to confirm that samples from impact sites were collected from an area of distinct experimental treatment are not publishable.

2.1.2. Sampling "immediately" after harvest could have occurred before harvest

Sampling "immediately" after harvest (Johnston et al.), based on their data for harvest timing, could have actually occurred before harvest since actual harvest dates are unknown, and sampling dates overlap the harvest period. Post-harvest sampling was reported to have taken place between Aug 1 and Nov 23, 2019 (Johnston et al., supplementary data). Sampling dates were provided, but the harvesting (treatment) dates for sites were not. Instead, a range of dates was provided for the harvesting treatment at all sites: "…all impact sites were harvested once between June and November 2019". It is possible, therefore, that "post harvest" sampling at a particular impact site was actually pre-harvest sampling. Because the date of harvest is unknown, the actual number of days elapsed after harvest, or the amount of time for biomass recovery after harvest, is also unknown for each impact site.

Table 1

Fixed effect three-way interaction LMM ANOVA table and contrasts for biomass. Results from a full linear mixed-effect model (including treatment, time and region as fixed effects, all lower level fixed effect interactions, and a site random effect) testing the impact of rockweed harvest on the average site rockweed biomass. The significance levels ($P \leq 0.05$ in bold) are calculated with F-statistics using Type III sum-of-squares and Kenward–Roger approximations for degrees of freedom. The contrasts which represent the effect of treatment on (top to bottom) harvest impacts, post-harvest growth, and one-year recovery, respectively, may be misleading due to involvement in interactions (red note was produced by the R software).

Fixed Effects	Sum Sq	Mean Sq	NumDF	DenDF	F value	Pr(>F)
Treatment	3.9860	3.9860	1	30	0.4685	0.4989
Time_Period	111.2838	55.6419	2	60	6.5395	**0.0027**
Region	91.8794	30.6265	3	30	3.5995	**0.0247**
Treatment × Time_Period	46.0151	23.0075	2	60	2.7040	0.0751
Treatment × Region	207.8142	69.2714	3	30	8.1414	**0.0004**
Time_Period × Region	58.3952	9.7325	6	60	1.1438	0.3485
Treatment × Time_Period × Region	62.8388	10.4731	6	60	1.2309	0.3034

Random Effects	Variance
Residual	8.51
Site	0.77

NOTE: Results may be misleading due to involvement in interactions

Treatment pairwise	Time pairwise	Estimate	SE	df	*t*	P
Control – Impact	Pre – Harvest	-2.72	1.39	60	-1.96	**0.05**
Control − Impact	Harvest − Post	2.86	1.39	60	2.06	**0.04**
Control − Impact	Pre − Post	0.14	1.39	60	0.10	0.92

Marginal R^2: 0.392 Conditional R^2: 0.442

2.1.3. Conflict of interest in research partners requires verification of harvest parameters

Conflict of interest in research partners required verification of harvest, harvest dates and harvest intensity, but verification was mostly lacking. Rockweed companies with financial interests in the outcome of the study were key players in this study. These companies controlled key elements of the design and the execution of this study. Key pieces of information - about whether a harvest occurred and, if it did, when it occurred - were unverified for 63% (12 of 19) of the "impact" sites.

The harvest companies helped select the study sites. Then, they or the harvesters working for them, decided where, when, and with what intensity, to cut the rockweed at "impact" sites. The eight names listed in the acknowledgements without affiliation are the names of owners or employees of four companies that cut and process Maine rockweed. By Maine law, after 2018 these companies require landowner permission to cut rockweed. Thus, in order for their businesses to thrive, they must convince landowners (and regulators) that rockweed harvesting does not negatively impact the rockweed beds.

The rockweed companies had financial interests in the results and in the conclusions of this study. They also strongly influenced the study's design, (i.e. they helped select the study sites). They controlled the project's execution: (1) whether the "impact" sites were actually cut; (2) whether the control or impact sites had been cut in the 3 years prior to the study; (3) whether the control areas remained uncut for the full, 3-year study period; and (4) whether the harvesters cut rockweed in impact sites using practices and intensities typical for commercial harvests.

Since the harvest company research partners benefit financially from a negative outcome of this study (no difference between control sites and impact sites), researchers should have verified that harvest treatments took place, where in the site, when and to what degree (amount of biomass removed from a site) they took place. Instead, Johnston et al. apparently neither verified that all "impact" sites had indeed been harvested nor did they know or record when, where in the site, or how intensely the "impact" sites were harvested. Researchers observed harvest at only 7 out of 19 (37%) impact sites (Johnston et al.).

Fig. 1. Rockweed stipe cut in 2019.
There are four annual air bladders (1–4) (MacFarlane, 1933) beyond the sharp slanted cut on the stipe. Commercial rockweed harvesting took place on this ledge (Pembroke, ME, USA; 44.920387, -67.139510) in 2019 (unpublished data). Photographed 6 June 2023.

We requested the locations of study sites to externally verify that harvests had taken place at "impact" sites. This is possible to confirm years after harvest, because harvest marks on rockweed fronds are still visible, and the annual bladder formation makes it possible to date the cuts (Fig. 1). The senior author (Johnston et al.) declined to share any study site locations with us (email to the senior author, February 26, 2023) so we were unable to verify harvests at impact sites.

Johnston et al. also provided no verification for the pre-conditions of the rockweed beds studied: that 1) all study sites had not been harvested in the three years prior to the study (2015–2017), and 2) control sites were not harvested during the study (2018–2020). Rather than researcher confirmation of (1) and (2), the authors relied on company assurances of (1) and (2). However, companies could not have known the past history of the beds or have been sure that the control sites were not harvested during the experiment: they do not lease or control rockweed beds, and licensed harvesters in Maine have equal access to all rockweed beds. Harvesters for the company that was assigned to the majority (28/38 or 74%) of the experimental sites are usually not employees, but independent contractors, and therefore do not have to follow company directives about where, when, and how hard to harvest. Indeed, the Johnston et al. data reveal that many control sites *lost* biomass between pre-harvest and harvest (Johnston et al., 2023, supplemental data), which is the time period that rockweed biomass should have increased or stayed the same.

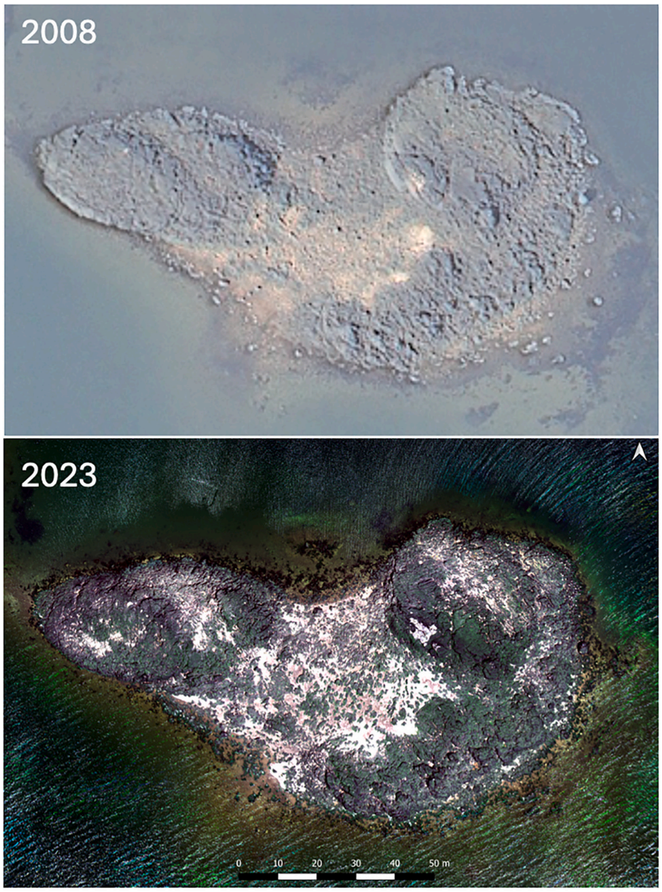


Fig. 2. Rockweed ledge in Pembroke, Maine, USA (Cobscook Bay, 44.915019, -67.115913) with *Ascophyllum* cover.
Repeated rockweed harvests there from 2021 through 2023 have resulted in cut stipes and rockweed biomass loss (white areas on east and west "lobes" of the ledge). Image sources: 2008: High resolution ortho imagery (https://earthexplorer.usgs.gov); 2023: esri.comRGB orthomosaic from multispectral drone imagery (NearView LLC).

Finally, harvest intensities in the harvested sites were not measured directly and it is unlikely that they all were typical of current commercial harvests (intense harvest shown in Fig. 2) in Maine. Did the harvesters do one short pass vs. multiple passes per bed? No information is provided about whether there was one boat vs. multiple boats, or one hour vs. several hours of harvest, or one short pass vs. multiple passes per bed at a site. Weights of biomass removed were not included in Johnston et al., suggesting that the researchers did not have these weight data. Instead, an indirect harvest intensity value was derived from a "pre-harvest to post-harvest" biomass change. As previously mentioned in section 2.1.1, Johnston, et al. acknowledge that researchers did not ensure that sampling took place in the harvested area of a study site. Therefore, an estimate of biomass change based on sample data from the rockweed bed, data that could have come from unharvested areas of the site, is not meaningful.

Evidence suggests that harvest intensity for their study site *was* less than is typical in Maine since 2019. The authors state without explanation that companies harvested beds at "impact" sites with practices and harvest intensities that replicate "typical" commercial harvests without defining "typical". However, an information sheet provided in 2018 to prospective landowners in the study (Klemmer, 2018) shows that the intensities of the harvests conducted for this study were *not* typical of current commercial harvests in Maine. Landowners were informed that the harvesters would be on their properties for only one day; whereas the commercial harvests we have observed since 2019 usually involve either multiple rake harvesters spending multiple days harvesting one site or a single machine harvester boat returning day after day to spend up to 6 h each day cutting at the same site (pers observation; unpublished data). This intensity of harvest effort can result in visually obvious swaths of bare or thin areas in the rockweed bed (Fig. 2.).

Since Johnston et al. conclude that the likelihood of rockweed bed "recovery" is lower at more intensely harvested sites (Fegley, 2001 also noted this), it is crucial that the development of Maine's harvest policy reflects actual harvest intensity. Rockweed harvest patterns changed strikingly in 2019, after Maine's Supreme Judicial Court clarified that harvesters must obtain landowner permission to harvest rockweed (Seeley, personal observation). It seems likely that impact sites in the Johnston et al. study were not all harvested at levels that are typical of current, post 2018 commercial harvests in Maine.

2.2. Incomplete statistical analysis with inappropriate inferential conclusions

2.2.1. Lack of random assignment and selection

Johnston et al. state: "we assigned treatment type (control or impact) to each site." This statement, however, is contradicted in the following sentence which states "landowner permissions to harvest rockweed prevented a fully spatially random treatment assignment, but we ensured that there was a spatial mixture of control (N = 19) and impact (N = 19) sites within each of the five predefined regions." In other words, the treatment was not randomly assigned to each site. Instead, some number of landowners, "x", refused the harvest treatment, and the treatment type was randomly assigned to the remaining (38 - x) sites so that the proportion of sites receiving each treatment was ~50% within a region. This lack of full randomization is often the case in environmental BACI designs (Green, 1979; Stewart-Oaten and Bence, 2001, as cited by Seger et al., 2021), but it limits the capacity for causal inference, and in this case, the ability to apply the results of the study to the larger statewide population of rockweed beds.

Additionally, Johnston et al. stated that two outlier sites were omitted from the final analysis. Both of these outlier sites were impact sites (Johnston et al., Fig. S1, C and D), and at least one of these sites was excluded based on harvest year data. This implies that, prior to the elimination of the outliers, either 1) the impact and control treatments were allocated such that the mixture of control ($N = 19$) and impact ($N = 21$) was unbalanced, or 2) the mixture was balanced with 21 sites in each group and when the two outlier impact sites were eliminated, two control sites were also eliminated to achieve a balanced design. The latter is not sound practice because eliminating sites to achieve a balanced design should not be considered an option in environmental effects monitoring as it can introduce statistical bias (Smokorowski and Randall, 2017).

According to a public presentation in the second year of the three year study (Webber, 2019), the Johnston et al. experimental design included more study sites and a more thorough sampling design: 54 sampling sites (30 harvest, 24 control) and data from transects in high, mid and low rockweed zones (rather than just the mid zone). In later public presentations after data collection was complete (Webber, 2021; Webber, 2022), the design included 45 sites (22 harvest, 23 control). The final publication had only 40 sites, 38 of which were used in the analysis (19 harvest and 19 control). The periodic study redesigns are unexplained in the final publication.

Lastly, transects were haphazardly chosen, as opposed to being randomly selected, and it is impossible to determine how this sample of convenience may have biased results. Furthermore, the three rockweed individuals measured for height were also haphazardly selected and "if the longest frond significantly overestimated canopy … we measured the length of the tallest frond in the group that represented the top of the canopy" (Johnston et al.). Control sites are more likely to have atypically long fronds than harvested sites, thus, the subjective replacement of these long frond individual heights with the heights of shorter individuals will be reflected disproportionately in the control site data and bias the treatment and control group comparisons.

2.2.2. Spatial heterogeneity in treatment application

Harvest spatial heterogeneity is the crux of the argument Johnston et al. provide as justification for the need for whole-bed analysis. Spatial patterns are usually divided into three types: random, aggregated, or regular (Begon et al., 1996, as cited in Vinatier et al., 2010). Distribution patterns may also be of a gradient type (Judas et al., 2002, as cited in Vinatier et al., 2010). In this case it is likely that, in addition to a 2-dimensional spatial pattern, there is a harvest-intensity gradient as well.

In the Johnston et al. study, the experimental unit is a site. The authors define "a rockweed bed at the scale of the harvest event in this study" (i.e. a study site) which implies that the area of one rockweed bed is equivalent to the area of one site, which is, in turn, equivalent to the area of a "harvest event," i.e. the treatment. A fundamental definition in experimental design is that an experimental unit is the unit to which one treatment is applied. In this experiment, however, the treatment, "harvesting", was not applied to the experimental unit, "site". It was, instead, only applied to an unknown sub-area of the site and with an unknown intensity. This is a crucial issue in the evaluation of the statistical methodology, and the subsequent interpretation of the results.

Ecological field experiments must be adequately designed according to the type and the scale of heterogeneity of concern (Dutilleul, 1993). Thus, a critical first step in this non-standard situation would be to determine the spatially heterogeneous manner in which the treatment was being applied to the experimental unit. This heterogeneity, however, is not characterized in any quantifiable way. A single image of an intertidal zone (Fig. S3, Johnston et al.) is the only evidence provided to illustrate the harvest spatial heterogeneity, but it is impossible to determine from a single ground photo the scale, pattern or degree of a harvesting event. There are methods for characterizing spatial heterogeneity, but none of these methods were used prior to the design and implementation of the sampling protocol in Johnston et al. The authors do acknowledge that there would be value in doing this in the future.

Johnston et al. use the results from a contingency table analysis to argue that two haphazardly located transect subsamples (the bare minimum needed to calculate within-site variability) were sufficient to provide estimates of average biomass at the rockweed bed-scale by virtue of the "high replication among each treatment", despite the lack of spatial overlap between the transect subsamples and the harvested area within the site. This is a circular argument because without a better understanding of the nature of the spatial heterogeneity of the treatment application, it is not possible to determine what constitutes "high replication." In general, high replication means collecting a sample that is large enough to iron out the noise due to random variation so the treatment effect, if it exists, can be detected with confidence. Determining if the amount of replication is sufficient for detecting the treatment effect requires a power analysis. A power analysis would require: a) quantification of an ecologically meaningful difference, and b) estimation of the population variability. Neither (a), (b), or a power analysis is provided.

2.2.3. Inappropriate inferential conclusions

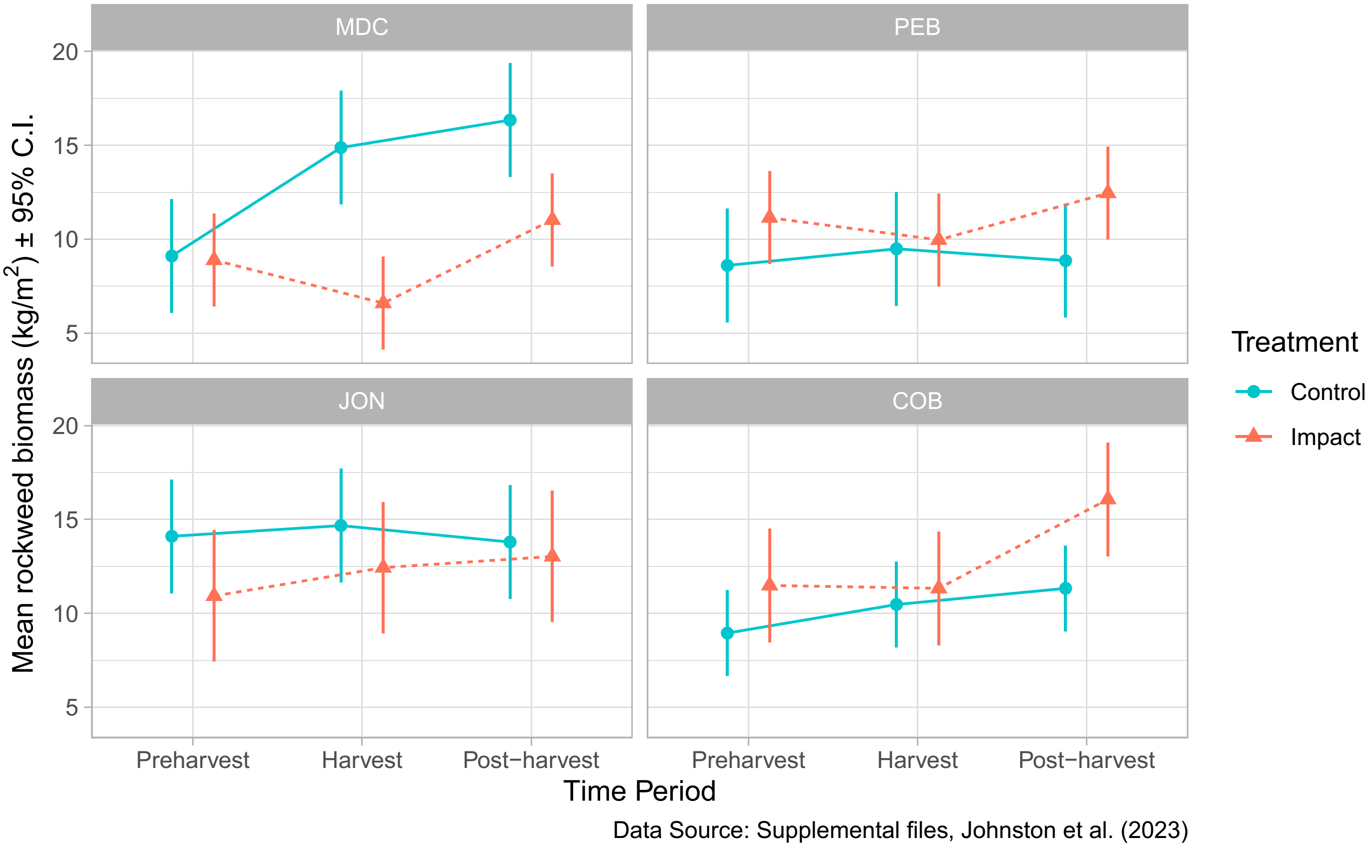
Johnston et al. drew conclusions, based on a large *p*-value, regarding the truth of the null hypothesis of "no harvest treatment effect." However, a key statistical principle is that large *p*-values do not provide evidence of the truth of the null hypothesis. It is critical to prospectively establish a biologically meaningful target effect size and power the study so it is likely to detect the target effect size, if it exists.

In the absence of these planning steps before the experiment took place, we are left not knowing if statistically undetectable biomass change one year after harvest (post-harvest compared to pre harvest) is due to harvest having no impact on biomass after one year, as Johnston et al. conclude, or, equally plausible, the study did not have enough power to reject the null hypothesis of no change between post harvest and pre harvest.

In general, when a *P*-value is large and the null hypothesis is not rejected, the correct conclusion is that the observed set of data points do not provide evidence in favor of the alternative hypothesis. Johnston et al. conclude "our data suggest that recovery, especially in biomass, can occur within a single year at the bed-scale using current commercial methods." The correct statistical conclusion is: "our data do not provide evidence of a decline in biomass one year after harvest." The danger lies in making the unfounded leap from the failure to reject the null hypothesis of "no treatment effect" to the conclusion reached by Johnston et al.

Understanding the difference between the two statements requires an understanding of what *P*-values do and don't tell us. A P-value is calculated under the assumption that the null hypothesis is true and is a function of 1) the difference between the observed data and the null hypothesis, 2) the size of the sample, and 3) the observed variability. The American Statistical Association (ASA) statement on *p*-Values (Wasserstein and Lazar, 2016) states unequivocally that "P-values do not measure the probability that the studied hypothesis is true" and that researchers should not attempt "to turn a p-value into a statement about the truth of a null hypothesis." They also explain that "large effects may produce unimpressive p-values if the sample size is small or measurements are imprecise."

Given that hypothesis test results that favor the interpretation of biomass returning to pre-harvest levels in one year relies on negative evidence (i.e. a large P-value resulting in the failure to reject the null hypothesis of no harvesting effect), it is critical to prospectively establish a biologically meaningful target effect size that is likely to be detected if



Data Source: Supplemental files, Johnston et al. (2023)

Fig. 3. Linear mixed model three-way treatment × time × region interaction plot.
Mean rockweed biomass across the three time periods in each region (four panels) and for each treatment group (two lines in each panel). In the Midcoast region panel, the error bars for the control and treatment lines do not overlap at the harvest or post harvest time points indicating there are significant differences between the control and impact groups at both of these time points. In all three remaining panels (regions), and at all three time points, the error bars for the control and treatment lines do overlap, indicating there are not significant differences at any of three time points, including the harvest year where there should have been an observable difference if the harvest treatment was detectable. The key point is that in the only region where the treatment was detectable, the biomass did not recover. Abbreviations: 23 MDC = Midcoast, PEB = Penobscot, JON = Jonesport, and COB = Cobscook.

it exists. It follows that if the target effect size cannot be detected, it is imperative to power the study accordingly (Lenth, 2007). There is no other way to distinguish between whether or not harvesting had no effect, or if the study was underpowered.

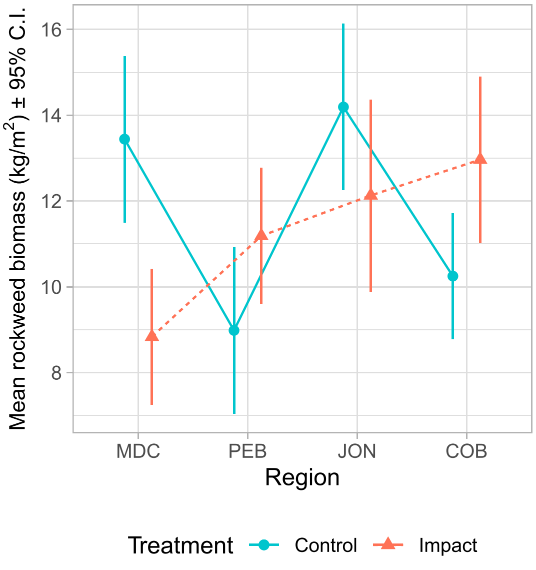
Johnston et al. neither prospectively established a biologically meaningful target effect size, nor took steps to power the study appropriately. Therefore, Johnston et al. should not conclude that "Mean rockweed biomass recovered to pre-harvest values after one year of recovery."

2.2.4. Regional differences in the linear mixed model (LMM)

Johnston et al. state that "region" is a fixed effect. Also, "region" is confounded with harvesting methodologies (mechanical vs. rake), harvesting companies, and data collection months, which further supports the inclusion of the region factor as a fixed effect. The regional contrasts presented in Table S2 (Johnston et al.) were constructed using a full LMM which included treatment, time and region as fixed effects (along with all lower level interactions) and site as a random effect. These contrasts are represented graphically in our Fig. 3 (similar to Johnston et al. Fig. 4B). These regional contrasts show that only in the Midcoast region was there a significant difference in the average biomass between the treatment and control sites immediately after harvest ($P = 0.002$), likewise for height ($P = 0.03$). That is to say, only in the Midcoast region was the treatment detectable.

Furthermore, these regional contrasts also show that only in the Midcoast region was there a significant difference in the average biomass between the treatment and control sites when comparing pre-harvest to post-harvest measurements ($P = 0.06$), likewise for height ($P = 0.002$). In other words, when the treatment was detectable, the rockweed beds did not recover.

It is worth noting that in none of the regions were there significant differences between the harvest year and the post-harvest year, which was the recovery period. This calls into question claims of biomass recovery (although, if the treatment was not detectable, there was nothing to recover from). The differing results between regions indicate the presence of a significant interaction between region and treatment which is shown graphically in Fig. 4.



Data Source: Supplemental files, Johnston et al. (2023)

Fig. 4. Linear mixed model two-way region × treatment interaction plot. Regional biomass means averaged over time periods for each treatment group (two lines). The key point is that the two lines cross each other indicating a significant region x treatment interaction. This is important because main factors, in this case treatment, cannot be fully evaluated in the presence of significant interactions, particularly cross-over interactions. Abbreviations: MDC = Midcoast, PEB = Penobscot, JON = Jonesport, and COB = Cobscook.

Johnston et al., however, chose to omit region as a fixed effect in the final step of their model analysis (Table 1, Johnston et al.), instead including it only as a random effect. This choice was consequential for their final conclusion. It appears that this modeling choice arose from a) the lack of a fixed region effect in an overall pre-harvest analysis (Table S1, Johnston et al.) and b) their goal of assessing "the average impact of harvest protocols presently operating in Maine… ." The number of impact and control sites was not balanced across regions; some regions had more control sites and some regions had more impact sites. Omitting region as a fixed effect created a balanced model structure (i.e. 19 impact sites and 19 control sites overall). However, by including region only as a random effect, Johnston et al. made an implicit assumption that the regions can be viewed as a sample from a larger population of regions, some of which have not been observed. In other words, the effect of the harvest treatment in any specific region is not consequential, and only the effect of the treatment on the larger state-wide population of rockweed beds is of interest.

Although the four regions are not representative of a larger population of regions, this approach (treating region only as a random factor) would be statistically defensible if the region main effect and region x treatment interaction terms were not significant in the full model (their Table 1). However, as the contrasts in their Table S2 (Johnston et al.) indicate, and as we demonstrate with the ANOVA table from the full model including region as a fixed effect (our Table 1), the main effect of region is significant ($P = 0.0247$) and, even more noteworthy, the most significant term in the model is the interaction between region and treatment ($P = 0.0004$). This indicates that the treatment effect was significantly different in different regions. Furthermore, in situations where significant interactions are present, main factors, in this case treatment, cannot be fully evaluated (Winer et al., 1991).

Our LMM analysis was performed with the lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017) packages in R version 4.3.0 (R Core Team, 2023). When the analogous contrasts presented in Table 1 of Johnston et al. are constructed based on the full model including region (our Table 1), the software returns the message: "NOTE: Results may be misleading due to involvement in interactions" along with the constructed contrasts.

In other words, overall conclusions regarding the general effect of the harvest treatment arrived at by pooling the data across regions could be misleading on a state-wide level and failure to qualify the conclusions with the effect of region could lead to potentially erroneous conclusions.

3. Key impacts of harvest not addressed

Impacts of harvest on biomass and height were only significant in the Midcoast area (Table S2, Johnston et al.). More importantly, harvest impacts are not limited to those on biomass and height. Rockweed beds provide a key ecosystem nutrient input through shedding of reproductive structures (receptacles), cast of fronds through seasonal breakage or storms, and epidermal shedding (Halat et al., 2015). Any discussion of rockweed harvest impacts in the context of ecosystem-based management (EBM) raised by Johnston et al., should, at a minimum, include these ecosystem impacts.

Fronds longer than 20–40 cm allocate growth to receptacles (Cousens, 1985); therefore, rockweed harvesting, which removes the distal part of the rockweed thallus, removes the part of the rockweed bed that will produce future receptacles. Receptacles are shed after gamete release in the last spring/early summer. They then decompose and become brown algal detritus, consumed by a wide range of organisms (Josselyn and Mathieson, 1978; Vadas et al., 2004). In addition, 10% of vegetative *Ascophyllum* frond biomass enters coastal waters each year as a result of epidermal shedding (Halat et al., 2015), in other words, biomass that also contributes to the detrital pool.

Combining estimates from shed frond biomass, frond removal from wave action, and receptacle decay suggests that rockweed harvesting produces a detrital deficit into the nearshore ecosystem of approximately 100% of the harvested amounts (Halat et al., 2015). Removing rockweed even at intensities of 17% (recommended annual biomass removal limit, Maine DMR-RPDT, 2014) of rockweed biomass results in a net decrease of NPP input to the ecosystem (Seeley and Schlesinger, 2012).

4. What is rockweed bed "recovery"?

Rockweed, *Ascophyllum nodosum*, is an intertidal "tree" (Olsen et al., 2010). A critical issue is how recovery is assessed. Is the return of biomass the most important measure of the rockweed forest recovery after commercial harvest? Fegley (2001) studied two years of *Ascophyllum* "recovery" after experimental cutting, which is one of the longer recovery studies of rockweed and its associated community to date. Fegley (2001) found that while harvested macroalgal populations may be considered to be "recovered" using measures of population biomass, biomass is highly variable and not a robust measure of "recovery", and recommended other measures (plant population and morphological characters) be used with biomass to more accurately assess "recovery".

We concur and would add measures of bed (forest) architecture to the list of characteristics used to assess "recovery" (length, circumference and density) especially, because they are much better predictors of community structure than biomass (Kay et al., 2016). Johnston et al. recognize that reliance on recovery assessments will vary by stakeholder group, with the harvest industry focused on biomass alone, while ecologists, wildlife managers and others focused on the rockweed ecosystem (NOSB, 2020) broaden the focus from biomass to other rockweed bed characteristics listed above.

Johnston et al. intended to bring a bed-scale perspective to rockweed habitat recovery in order to inform ecosystem-based management (EBM). For the reasons we have outlined above, we believe their approach in this paper does not inform EBM effectively. Ecosystem based management will be much better informed by broadening the focus from biomass recovery to measures of rockweed forest habitat recovery that affect the ecosystem, including recovery of the rockweed canopy. If management based on ecosystem goals is our aim, then despite recovering its biomass, a rockweed bed cannot be said to have truly "recovered."

Finally, we note the importance of examining the effect of repeat harvests: does any rockweed resilience to harvest erode with increasing frequency of harvest perturbation? Johnston et al. recognized that a critical factor in recovery is the interval between repeated harvests. "It is unclear how observed trends would change in years two and three of recovery, …We recognize that resource managers must think about harvest intervals and recovery of the resource at multi-year and decadal scales…". We agree, especially since new harvest patterns emerged in Maine after 2018 that have resulted in harvesters returning repeatedly to the same sites annually, and repeat harvests at the same site within one harvest season.

5. Conclusion and policy warning

The turnover time of *Ascophyllum nodosum* biomass in undisturbed populations from two studies in Maine is about 2.3 (Adey et al., 2020) to 2.0 years (Vadas et al., 2004). Studies in ME and NB Canada indicated that rockweed biomass takes two to three years to recover to pre-harvest levels (Fegley, 2001; Sharp and Pringle, 1990). The marine resource management policy implications of any conclusions about rapid return of rockweed biomass are significant. The finding, therefore, that under harvest conditions biomass returns in one year across the state of Maine (Johnston et al.) is an extraordinary conclusion requiring extraordinary proof.

We find no such proof in Johnston et al., because of the fundamental problems in this study discussed above. Rather than "provide resource managers with a bed-scale perspective that can inform EBM approaches," this paper provides no credible evidence that the way industry typically harvests rockweed beds in Maine allows a quick, one year recovery of rockweed bed biomass: the only regions where biomass quickly returned to pre-harvest levels were the regions where the harvest treatment was undetectable. In the one experimental region that had a detectable harvest of biomass, neither rockweed height nor biomass returned to pre-harvest values one year after the cutting. Rockweed beds in Maine cannot be said to "recover" from commercial harvest in one year based on the study in Johnston et al.

Rockweed is a foundational species in the rocky intertidal food web (Adey et al., 2020; Seeley and Schlesinger, 2012) and an ecosystem engineer (Dudgeon and Petraitis, 2005). Rockweed also contributes critical nearshore ecosystem inputs (Vadas et al., 2004). It is crucial that we get it right when we assess all the impacts of commercial-scale harvests of rockweed, for these conclusions become the basis for policy decisions that not only affect habitat quality, but the commercial fisheries and wildlife that depend on these rockweed beds as habitat (Seeley and Schlesinger, 2012).

Problems with the Johnston et al. study discussed here led to improper conclusions. Those improper conclusions have already misled resource managers, landowners and the public about a rapid return of biomass to harvested rockweed beds. Most concerning, this paper creates a false foundation for legislators and regulators crafting marine policy on commercial rockweed harvests in Maine and throughout the North Atlantic.

CRediT authorship contribution statement

Robin Hadlock Seeley: Conceptualization, Supervision, Writing – original draft, Writing – review & editing, Visualization. **Sarah Hardy:** Methodology, Formal analysis, Writing – review & editing, Visualization. **Nancy K. Prentiss:** Conceptualization, Writing – original draft, Writing – review & editing, Visualization. **Walter H. Adey:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jembe.2023.151984.

References

Adey, W.H., 1982. A Resource Assessment of Gouldsboro Bay, Maine: Report to the National Oceanographic and Atmospheric Administration, Marine Sanctuary Program, p. 100. https://repository.library.noaa.gov/view/noaa/50012.

Adey, W.H., Hayek, L.C., 2011. Elucidating marine biogeography with macrophytes: quantitative analysis of the North Atlantic supports the thermogeographic model and demonstrates a distinct subarctic region in the northwestern Atlantic. Northeast. Nat. 18, 1–128. https://doi.org/10.1656/045.018.m801.

Adey, W.H., Suskiewicz, T.S., Rasher, D.B., 2020. Marine ecosystem analysis of Gouldsboro and Dyer Bays, Maine. Smithson. Contrib. Mar. Sci. 43, 192. https://doi.org/10.5479/si.11950329.

Bates, D., Mächler, M., Bolker, B., Walker, S., 2015. Fitting linear mixed-effects models using lme4. J. Stat. Softw. 67 (1), 1–48. https://doi.org/10.18637/jss.v067.i01.

Begon, M., Harper, J.L., Townsend, C.R., 1996. Ecology: Individuals, Populations and Communities, third ed. Blackwell Science Ltd., Oxford, p. 1068.

Cousens, R., 1985. Frond size distributions and the effects of the algal canopy on the behavior of *Ascophyllum nodosum*. J. Exp. Mar. Biol. Ecol. 92 (2–3), 231–249. https://doi.org/10.1016/0022-0981(85)90097-8.

Dudgeon, S., Petraitis, P.S., 2005. First year demography of the foundation species, *Ascophyllum nodosum*, and its community implications. Oikos. 109, 405–415. https://www.jstor.org/stable/3548759.

Dutilleul, P., 1993. Spatial heterogeneity and the design of ecological field experiments. Ecology. 74 (6), 1646–1658. https://doi.org/10.2307/1939923.

Fegley, J.C., 2001. Ecological Implications of Rockweed, *Ascophyllum nodosum* (L.) le Jolis, Harvesting. Ph.D. thesis.. University of Maine, Orono, Maine https://digitalcommons.library.umaine.edu/cgi/viewcontent.cgi?article=1421&context=etd&httpsredir=1&referer=.

Green, R.H., 1979. Sampling Design and Statistical Methods for Environmental Biologists. John Wiley & Sons, New York, NY, p. 279.

Halat, L., Galway, M.E., Gitto, S., Garbary, D.J., 2015. Epidermal shedding in *Ascophyllum nodosum* (Phaeophyceae): seasonality, productivity and relationship to harvesting. Phycologia 54 (6), 599–608. https://doi.org/10.2216/15-32.1.

Johnston, E.M., Mittelstaedt, H.N., Braun, L.A., Muhlin, J.F., Olsen, B.J., Webber, H.M., Klemmer, A.J., 2023. Bed-scale impact and recovery of a commercially important intertidal seaweed. J. Exp. Mar. Biol. Ecol. 561 https://doi.org/10.1016/j.jembe.2023.151869.

Josselyn, M.N., Mathieson, A.C., 1978. Contribution of receptacles from the fucoid *Ascophyllum nodosum* to the detrital pool of a north temperate estuary. Estuaries. 1, 258–261. https://www.jstor.org/stable/1351529.

Judas, M., Dornieden, K., Strothmann, U., 2002. Distribution patterns of carabid beetle species at the landscape-level. J. Biogeogr. 29, 491–508. https://doi.org/10.1046/j.1365-2699.2002.00697.x.

Kay, L.M., Eddy, T.D., Schmidt, A.L., Lotze, H.K., 2016. Regional differences and linkage between canopy structure and community composition of rockweed habitats in Atlantic Canada. Mar. Biol. 163 (12), 1–16. https://doi.org/10.1007/s00227-016-3027-3.

Kerr, L.A., Kritzer, J.P., Cadrin, S.X., 2019. Strengths and limitations of before–after–control–impact analysis for testing the effects of marine protected areas on managed populations. ICES J. Mar. Sci. 76, 1039–1051. https://doi.org/10.1093/icesjms/fsz014.

Klemmer, A.J., 2018. Conserving Rockweed Animal Systems for a Sustainable Harvest: Frequently Asked Questions about the Fieldwork and Harvest. University of Maine. https://tinyurl.com/2h2z3reu (accessed 7 June 2023).

Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2017. lmerTest package: tests in linear mixed effects models. J. Stat. Softw. 82 (13), 1–26. https://www.jstatsoft.org/article/view/v082i13.

Lenth, R., 2007. Post Hoc Power: Tables and Commentary, The University of Iowa Department of Statistics and Actuarial Science Technical Report No. 378, p. 13. https://stat.uiowa.edu/sites/stat.uiowa.edu/files/techrep/tr378.pdf.

MacFarlane, C., 1933. Observations on the annual growth of *Ascophyllum nodosum*. Proceed. Nova Scotian Inst. Sci. 18, 27–33. https://dalspace.library.dal.ca/bitstream/handle/10222/13270/v18_p2_a2_MacFarlane_observations_annual_growth_Ascophyllum_nodosum.pdf?sequence=1&isAllowed=y.

Maine DMR-RPDT, 2014. (Department of Marine Resources-Rockweed Plan Development Team). Fishery Management Plan for Rockweed (*Ascophyllum nodosum*). DMR, Augusta: Maine. https://www.maine.gov/dmr/sites/maine.gov.dmr/files/docs/DMRRockweedFMPJan2014.pdf.

NOSB, 2020. Formal Recommendation of the National Organic Standards Board (United States Department of Agriculture): Marine Macroalgae in Crop Fertility Inputs. https://www.ams.usda.gov/sites/default/files/media/MSMarineMaterialsRec_webpost.pdf.

Olsen, J.L., Fzechman, F.W., Hoarau, G., Coyer, J.A., Stam, W.T., Valero, M., Aberg, P., 2010. The phylogeographic architecture of the fucoid seaweed *Ascophyllum nodosum*: an intertidal marine tree and survivor of more than one glacial-interglacial cycle. J. Biogeogr. 37, 842–856. https://doi.org/10.1111/j.1365-2699.2009.02262.x.

R Core Team, 2023. R: A Language and Environment for Statistical Computing. The R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org (accessed 1 October, 2023).

Seeley, R.H., 1986. Intense natural selection caused a rapid morphological transition in a living marine snail. Proc. Natl. Acad. Sci. U. S. A. 83 (18), 6897–6901. https://doi.org/10.1073/pnas.83.18.6897.

Seeley, R.H., Schlesinger, W.H., 2012. Sustainable seaweed cutting? The rockweed (*Ascophyllum nodosum*) industry of Maine and the maritime provinces. Ann. N. Y. Acad. Sci. 1249, 84–103. https://doi.org/10.1111/j.1749-6632.2012.06443.x.

Seger, K., Sousa-Lima, R., Schmitter-Soto, J., Urban, E., 2021. Editorial: before-after control-impact (BACI) studies in the ocean. Front. Mar. Sci. 8 https://doi.org/10.3389/fmars.2021.787959.

Sharp, G.J., Pringle, J.D., 1990. Ecological impact of marine plant harvesting in the Northwest Atlantic: a review. Hydrobiologia 204 (205), 17–24. https://doi.org/10.1007/BF00040210.

Smokorowski, K.E., Randall, R.G., 2017. Cautions on using the before-after-control-impact design in environmental effects monitoring programs. Facets. 2 (1), 212–232. https://doi.org/10.1139/facets-2016-0058.

Stewart-Oaten, A., Bence, J.R., 2001. Temporal and spatial variation in environmental impact assessment. Ecol. Monogr. 71, 305–339. https://doi.org/10.1890/0012-9615(2001)071[0305:TASVIE]2.0.CO;2.

Vadas, R.L., Wright, W.A., Beal, B.F., 2004. Biomass and productivity of intertidal rockweeds (*Ascophyllum nodosum* LeJolis) in Cobscook Bay. Northeast. Nat. 11 (2), 123–142. https://www.jstor.org/stable/60225652.

Vinatier, F., Tixier, P., Duyck, P.F., Lescourret, F., 2010. Factors and mechanisms explaining spatial heterogeneity: a review of methods for insect populations. Methods Ecol. Evol. 2 (1), 11–22. https://doi.org/10.1111/j.2041-210X.2010.00059.x.

Wasserstein, R., Lazar, N., 2016. The ASA statement on *p*-values: context, process, and purpose. Am. Stat. 70 (2), 129–133. https://doi.org/10.1080/00031305.2016.1154108.

Webber, H., 2019. Powerpoint Slides: Conserving rockweed Animal Systems for Sustainable Harvest. Univ. of Maine, Sea Grant, 2019 Beaches Conference. https://seagrant.umaine.edu/wp-content/uploads/sites/467/2019/08/2019-bc-webber-rockweed.pdf. (Accessed 15 May 2023).

Webber, H., 2021. Rockweed Research from the Bottom Up with Hannah Webber. [Webinar]. Harpswell Heritage Land Trust. https://www.youtube.com/watch?v=Fp7JfPPTYBk.

Webber, H., 2022. Adventures in Rockweed: Researching the Ecology of the Maine Coast. [Webinar]. Schoodic Institute. https://www.facebook.com/SchoodicInstitute/videos/297488599260006/?mibextid=zDhOQc.

Winer, B.J., Brown, D.R., Michels, K.M., 1991. Statistical Principles in Experimental Design (3rd Ed). McGraw-Hill, Inc, New York (928 pp).