

A Final Report
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**Sea Urchin Conservation Areas in Maine:
Winter Survey Results 2000-2003**

Richard A. Wahle

and

Julien Gaudette

Bigelow Laboratory for Ocean Sciences
McKown Point Road
West Boothbay Harbor, Maine 04575

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Executive Summary

In 1999 six sea urchin no-take marine protected areas (MPA's) were established along the Maine coast paired with nearby control sites that continued to be subject to harvesting. This report summarizes the results of winter surveys conducted to evaluate changes in sea urchin biomass, roe yield, and algal cover at 5 and 10 m depth at each site over a four year period. Results of complementary summer surveys assessing urchin biomass, algal cover, and larval settlement are reported in Vavrinec (2003).

Increases in sea urchin biomass and roe yield per unit area were observed at the Pemaquid Point MPA, where the closure clearly pre-empted harvesting depletion. At the control site near the Pemaquid MPA where harvesting continued, biomass declined precipitously and the benthic community shifted from urchin dominated "barrens" to kelp beds. At the two MPA's established in the York region, the sea urchin population had already been severely depleted several years earlier. No urchins were found at these sites and they were entirely dominated by kelp and other macroalgae. There we observed no recovery of urchins during the course of the study. At the Schoodic Point MPA, contrary to expectation, sea urchin biomass declined more rapidly within the MPA than at the control site, and eye witness accounts indicate poaching had been at least partly responsible. In the Jonesport region, sea urchin biomass was already at low levels when the two MPA's were established, but there was little change in biomass at any of the sites over the course of the study.

Gonad indices (roe weight as a percent of body weight) were inversely related to population density and depth. This is likely a result of food limitation as algal cover also declined significantly with density and depth. In spite of the diminished individual gonad mass at greater densities we observed a linear increase in roe yield per unit area of seabed with

increasing adult densities. The linear nature of the relationship over the observed range of adult biomass suggests there is a potential for greater population-level reproductive output at even the high-density sites.

Together with previous findings, our results suggest that MPA's may hold some promise as a management tool for the Maine sea urchin fishery. However, it will be necessary to weigh the benefits to be realized through MPA's relative to traditional management strategies. Specifically research is required to determine the size and number of conservation areas necessary to have a positive impact on yield, both inside and outside their boundaries. Furthermore, because of the dramatic impact that changes in population density have on reproductive performance, algal cover, and subsequent recruitment, research continues to be necessary to understand population dynamics of depleted populations.

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Introduction

Using areas closed to fishing as a strategy to rebuild fisheries has been a subject of intensifying research in recent years (Roberts et al. 2001, Botsford et al. 2003, Hasting and Botsford 2003, Lubchenco et al. 2003). Area closures have resulted in higher biomass of a variety of harvested fish and invertebrates worldwide (New Zealand: Cole and Keuskamp 1998, Shears and Babcock 2002, 2003; California: Lafferty and Kushner 2000; Kenya: Watson and Ormond 1994; the Mediterranean: Sala et al. 1998; the Caribbean: Smith and Berkes 1991, and New England: Murawski et al. 2000).

Encouraged by these and other successes, the harvesters and managers of the Maine sea urchin fishery have turned to marine protected areas (MPA's) as a promising tool to foster the recovery of populations depleted by harvesting. For a brief period in the 1990s the green sea urchin fishery in Maine had the distinction of being the state's second most valuable fishery, next to lobsters. Over the past decade and a half, however, sea urchin populations have been severely depleted, especially along Maine's southwestern coast (Chen and Hunter, 2003). Since the mid-1990's the fishery has been increasingly restricted by size limits, day-limits, and limited entry. In 1999 the Maine Department of Marine Resources Sea Urchin Zone Council agreed to support exploratory research to examine the efficacy of MPA's to mitigate harvesting impacts, and established six small MPA's closed to the taking of sea urchins

In most cases around the world MPA's have not been designed to protect sea urchins specifically. In fact, there are several cases in which sea urchin populations have suffered as a result of a trophic cascade in which protected consumer species, such as fishes and spiny lobsters, depleted sea urchin below levels found outside the protected areas (e.g., Watson and Ormond 1994, Sala and Zabala 1996, Cole and Keuskamp 1998, Lafferty and Kushner 2000,

Shears and Babcock 2002, 2003). In regions where sea urchin fisheries are economically important, however, there has been much interest in using marine reserves as a tool in a management strategy promoting sustainable yields (Smith and Berkes 1991, Quinn et al. 1993, Morgan et al. 1998, Lafferty and Kashner 2000, Morgan and Botsford 2001, Carter and VanBlaricom 2002).

Research on the Maine sea urchin MPA's was divided into summer and winter surveys led by separate research teams, the former intended to evaluate larval settlement and juvenile densities, the latter to evaluate roe yield just prior to the spawning season. Both surveys assessed sea urchin population densities, biomass, and algal cover. Results of the summer surveys are reported in Vavrinec (2003). The present report concerns the winter surveys. It contains findings on the degree to which sea urchin biomass, roe yield, and algal cover changed at the six MPA's relative to nearby control sites that continued to be subject to harvesting over the four year course of the study.

Materials and Methods

Study Sites

In the autumn of 1999 six sea urchin marine protected areas (MPA's) were closed to fishing along the Maine coast to evaluate whether the urchin populations would recover within their boundaries (Table 1). The areas were selected by DMR with the assistance of researchers, local harvesters and a public hearing process. Selection of the areas was determined by several criteria which included enforceability, previous history of dense urchin populations that were currently depleted, and the availability of prior scientific data. Six corresponding "control" areas were selected nearby the MPA's to enable comparison to sites that continued to be harvested

(Table 1). Two MPA-control site pairs were established in both the York and Jonesport regions; and single MPA-control pairs in the Pemaquid and Schoodic regions. The closed areas included 300 m of shoreline and subtidal seabed to the 20-30 m isobath. The corners of the areas were marked with conspicuous buoys. DMR circulated flyers indicating the location of the MPA's to all licensed harvesters.

Dive Surveys

Winter surveys began at MPA and control sites in Feb-March 2000 and ended in 2003. Winter surveys complemented annual summer surveys that began at some of the sites as early as 1994. Results of the summer surveys are given in companion reports (Vavrinec 2003, Steneck in prep.). Winter surveys were conducted to determine algal cover and urchin population densities as in the summer surveys, with the additional task of evaluating roe content just prior to the early spring spawning season. They were conducted in February and March each year advancing from south to north in accordance with and prior to the spawning season. For consistency, divers conducted surveys on ledge substrate at all locations, avoiding sediment or cobble-boulder habitat. Winter surveys were initially conducted only at a depth of 10-m (below MLW), the same depth as the summer surveys. From 2001 onward winter surveys were expanded to include a 5-m depth stratum at two sites in each region to better account for depth-related differences in the urchin populations, roe production, and algal cover.

Urchins were counted within 20 haphazardly tossed 1-m quadrats. The quadrats were subdivided into smaller $1/2$, $1/4$, and $1/16$ m² areas used for very dense populations. In the vast majority of cases urchins were counted within the full 1-m² area of the quadrat, but on occasion it was necessary to use a smaller area to ensure that divers would be able to complete the full

complement of 20 quadrats within a single dive. To assess size structure of the population, a sample of approximately 100 urchins was collected by taking the entire contents of whole quadrats until about 100 urchins were collected. This approach to evaluating size structure saved divers time measuring urchins underwater, and also served to provide the urchins needed to evaluate gonad mass. We planned to measure gonad mass of ten sea urchins per 10 mm test diameter class, starting with 20 mm urchins, the size urchins begin to mature. Where we fell short of ten urchins per size class, we augmented the sample by collecting additional urchins during the survey dive. Divers collected these urchins in a separate bag so as not to confound the collection used to determine size composition.

Divers estimated algal cover visually within each quadrat. Macroalgae were grouped into three broad categories: crusts (leathery and calcified forms), turf-forming (e.g., mostly *Condrus crispus* and other red-foliose forms), and canopy-forming types (e.g., mostly *Laminaria* spp., *Agarum cribosum*, *Codium fragile*). Sea urchin “barrens” are usually dominated by crustose forms, and the cover of fleshy forms has often been reported to be inversely related to urchin abundance (Keats et al. 1984, Wahle and Peckham 1999). As in prior studies, to evaluate the urchin biomass-algal cover relationship here we combined the cover estimates of turf- and canopy-forming algae. The combined estimate could potentially be as high as 200% because of the multi-layer nature of algal cover.

Gonad Analysis

In the laboratory, sea urchins were blotted off with a paper towel to remove excess water. Urchin test diameter was measured with steel digital calipers to the nearest 0.1 mm. The urchin was then weighed on an electronic scale to the nearest 0.01 g, and then dissected to remove the

roe. Gonads were blotted on paper towel to remove excess moisture and then weighed. Gonad index is expressed as the gonad mass as proportion of whole body mass.

Biomass estimates per square meter for each study site and depth were derived from population density estimates by taking the body mass calculated for the mid-point of each 10 mm size class, multiplying by the density of urchins in the size class, and summing across all size classes. The test diameter-to-body mass relationship of urchins from our samples was determined by least squares regression to be:

$$y = 0.000769x^{2.838338} \quad (r^2 = 0.995)$$

where y is body mass in grams, and x is test diameter in mm.

We report sea urchin biomass by site and depth for urchins ≥ 20 and ≥ 50 mm test diameter. The onset of maturity is approximately 20 mm in Maine (Vadas and Beal 1999), and the legal harvestable size was 50 mm, although it increased to 52 mm in 2001. To estimate the roe yield in grams per m^2 , the biomass estimate was multiplied by the average gonad index. Gonad Index and biomass are reported only for urchins ≥ 20 mm diameter.

For each site yearly means of urchin biomass per m^2 , gonad index, gonad mass per m^2 , and algal cover are presented with 95% confidence intervals. Site differences and temporal changes were evaluated on the basis of the degree to which confidence intervals overlap. Data are presented for each MPA-control site pair, and we interpret the performance of the MPA relative to changes occurring at the nearest control site. Since no winter surveys were conducted prior to establishing the MPA's, it was not possible to make before-after comparisons within the MPA's. We therefore restrict our analysis to the comparison of MPA's and controls over the course of the closure period.

In addition we evaluated the relationship between sea urchin biomass and algal cover, gonad index and gonad mass per unit area. For this analysis we pooled the data from all sites and years and conducted a least-squares linear regression for the 5 and 10-m depths separately.

Roe Quality

In 2001 roe quality was evaluated for legal size urchins (≥ 50 mm test diameter) by commercial standards at all sites and at both depths. Roe quality was evaluated by a subjective index that judged color, texture, and degree of melting. A commercial buyer (P. Blais, Roeboat Enterprises, Inc., Boothbay Harbor, Maine) provided guidance in developing the index. The index was calculated as the mean of three scores given for the following criteria: extent of melting (score of 1, none; 2, some; 3, extensive - 'melted ice cream'), grain size (1, fine; 2, medium; 3, coarse), and gonad color (1, bright; 2, pale; 3, dark). Because industry prefers firm, fine grained and bright colored gonads, a lower score indicated better quality. Note that gonad volume did not enter into the score. For consistency in data collection only two individuals working together evaluated roe quality. Up to ten urchins were sampled for each site and depth. Evaluating roe quality was not continued beyond 2001 because of the similarity in quality across all sites.

Results

Summaries by Region

- *York Region:* No urchins have been found at either of the MPA's or control sites in the York region since the onset of the winter surveys in 2000 (Fig. 1a, 2a). Algal cover at these sites has averaged between 60 and 110% at both 5 and 10m depths during the winter, and has been

comprised largely of a red algal turf with interspersed kelp stipes that had undergone their winter die-back (Fig. 1b, 2b). No data are therefore available on the reproductive status of sea urchins in York during this period.

- *Pemaquid Region:* At the Pemaquid MPA legal urchins (≥ 50 mm test diameter) comprised more than half the biomass over the course of the study (Fig. 3a). At 5 m biomass was slightly less than at 10 m, but it more than tripled to 1500 g per m² by 2002, after which it dropped back to 1000 g per m² by 2003. Biomass at 10 m started at about 400 g per m² in 2000 and then more than doubled by 2002, after which it dropped back to 500g per m² in 2003. At the nearby control site (Thrumcap Island) legal and sublegal urchins were found in about equal proportions. At 5m urchin biomass was already quite low in 2001 (<100 g per m²), and dropped to zero within a year. At 10 m biomass started somewhat higher than at the MPA, but by 2003 the population of all urchins had dropped to near zero.

Changes in algal cover were generally commensurate with changes in urchin biomass at both the MPA and control sites (Fig. 3b). At the MPA at 5 m, where urchin biomass increased, algal cover dropped from about 90% to near zero; at 10 m where urchin biomass remained relatively high, algal cover started low and ended low. At the control site at 5m where urchin density was always low, algal cover was consistently over 100%; at 10 m, where the urchin population dropped dramatically, algal cover started low and ended at about 60%.

Gonad index generally followed suit (Fig. 3c). That is, in the MPA at 5 m, where biomass increased sharply gonad indices declined, but at 10 m gonad indices remained constant where biomass stayed relatively constant. In the control site at 5 m, where urchin biomass was low and food supply high from the onset, gonad indices were consistently high, but at 10 m,

where urchin numbers sharply declined and algal cover increased, gonad indices nearly doubled to 25%.

Despite the apparent response of individual gonad mass to density and food supply, overall gonad yield per unit area remained largely proportional to urchin biomass (Fig. 3d). Thus, even though individual gonad mass had nearly doubled at 10 m in the control area, that increase was insufficient to compensate for the decline in urchin abundance.

- *Schoodic Region:* At the Schoodic MPA legal urchins comprised the majority of the biomass. Urchin biomass there held near or above 500 g per m² at both 5 and 10 m until 2003 when it dropped precipitously to only a few grams per m² (Fig. 4a). At the control site (Little Moose Island) sublegal urchins comprised the greater part of the biomass (Fig. 4a). Biomass there started at nearly the same level as at the MPA, and despite a substantial increase at both depths in 2002, by 2003 there had been little or no gain over 2001 levels.

Algal cover was consistently lower at the relatively urchin-rich control area than at the MPA (Fig. 4b). In spite of an increase in urchin density at both depths in 2002, algal cover also increased that year, although it dropped back again by 2003.

Gonad indices were consistently a few percent higher in the MPA than the control area, but the difference changed little over the course of the study (Fig. 4c). Gonad yield per unit area was somewhat higher in the MPA but as urchin biomass dropped in there in the ensuing years, roe yield fell below that of the control site by 2003 (Fig. 4d).

- *Jonesport Region:* At the Ram Island MPA in Jonesport legal urchins dominated the population at 5 m, and sublegal urchins dominated at 10 m; at both depths urchin biomass

remained relatively constant at a few hundred g per m² over the course of the study (Fig 5a). At the control site legal urchins dominated the population, and biomass there started at about the same level as at the MPA at both depths (Fig. 5a). But over the course of the study biomass remained low at 5 m and declined steadily at 10 m.

Algal cover at 5 m at Ram Island MPA and its control varied from 50 to 120% over the period. At 10 m algal cover started near zero at both sites, but increased to nearly 50% by 2003 at the control site as urchin biomass steadily declined (Fig. 5b).

Gonad indices were consistently greater than 15% at 5 m and less than 15% at 10 m at both MPA and control site (Fig. 5c). Because neither site changed much with respect to urchin biomass or individual gonad indices, there was little change in roe yield per area over the course of the study.

Surveys at the other pair of Jonesport sites were only conducted at 10 m depth. Urchin biomass at both the MPA (Sea Duck Island) and its control site (Little Drisko Island) urchin biomass was very low, but virtually all of legal size, and changed little over the course of the study (Fig. 6a). Consequently algal cover (Fig. 6b) and gonad indices (Fig. 6c) were relatively high compared to the more populated sites at Ram Island. As a result of the low population density, roe yield per unit area remained consistently low (Fig. 6d).

Sea Urchin Biomass, Algal cover, and Reproductive Performance

Taking all years and sites together we found a significant inverse relationship between sea urchin biomass and both algal cover (Fig. 7a) and gonad index (Fig. 7b), as has been reported elsewhere. Both algal cover and gonad indices averaged higher at the shallower depth. Gonad yield per unit area scaled significantly linearly with biomass with no indication of an asymptote

at high levels of biomass (Fig. 7c). This was true at both depths, although roe yield increased more rapidly with biomass at 5 than at 10 m.

Roe Quality

Commercial roe quality of sea urchins ≥ 50 mm was slightly better (by a difference of 0.1-0.5 index points) in deep than shallow zones at all sites except Schoodic where it was slightly worse (-0.1; Fig. 8).

At 5 m roe quality was quite similar among all sites for both sexes combined (2.0-2.3), for males (2.1-2.5), and for females (1.9-2.2). At shallow sites gonad quality was better in females than males at all sites (by a 0.2-0.5 point difference).

At 10 m roe quality was also quite similar among all sites for both sexes combined (1.8-2.3) and for males (2.1-2.6), but for females, Ram Island had a better mean score (1.5) than the other sites (1.8-2.2). Gonad quality was better in females than males at all sites (by a 0.2-0.7 point difference).

Discussion

MPA Performance

The winter surveys of the MPA's provided corroboration of abundance patterns observed in the summer surveys at 10 m, as well as additional data on abundance at a shallower depth (5m). They also provided the only measure available of roe yield and potential reproductive performance of these populations.

Below we interpret our findings for each MPA in light of the summer surveys and other relevant information. Changes in sea urchin biomass and algal cover observed over four years of

winter surveys are generally consistent with those observed in the summer surveys (Vavrinec 2003), although a few differences were borne out. As might be expected, in general, algal cover, particularly kelp, was higher in the summer surveys when algal biomass is near peak along the coast.

In the York region sea urchins had been depleted long before the MPA's were established. Having started surveys of the York sites several years prior to the establishment of the MPA's, Vavrinec (2003) reported that urchin biomass was already low in surveys conducted in the mid-1990s, but by 1996 at all sites densities had fallen to levels undetectable by our quadrat methods, and the switchover to fleshy algae had occurred. Because commercial harvesting had effectively ceased in the area, the closing of Eastern Head and Seal Head to harvesting in late 1999 was too late to be effective at re-establishing sea urchin populations.

The Pemaquid MPA may be considered to have been effective to the extent that (1) its establishment pre-empted the process that had already occurred in York, and (2) urchin biomass either increased (5m) or held constant (10 m) within its boundaries. The summer surveys report a very slight decline at 10m (Vavrinec 2003, Steneck unpublished). But no decline within the MPA was as great as at the control site (Thrumcap Island) that continued to be subject to harvesting. Because enforcement and compliance was considered to be quite good at the Pemaquid MPA, we believe it is more likely any losses were a result of natural mortality or emigration (Vavrinec 2003). Thus the Pemaquid MPA may have been modestly effective at enhancing sea urchin biomass and roe yield over the course of the study.

At the Schoodic MPA, contrary to expectation, sea urchin biomass declined more quickly than in the harvested control site (Little Moose Island). This was true for both the winter and summer surveys (Vavrinec 2003, Steneck unpublished). On the basis of eye witness accounts

Vavrinec (2003) surmised that the sharp decline at this MPA might have been the result of poaching. Had the poachers been selectively removing legal urchins, we might have expected the losses to be greatest among legal sized urchins. However, we observed equal declines in legal and sublegal urchins. If poachers were the cause of the decline, our data suggest they were being non-selective in their harvesting, only culling out sublegal urchins after the fact. At the nearby control site (Little Moose Island) from the outset of the project legal urchins comprised a much smaller percent of the population than we saw at the MPA, and subsequent declines were more gradual. In short, protection from harvesting did not have the desired effect, possibly because of poor enforcement and compliance.

In the Jonesport region there was little change in biomass at either the MPA or the control areas as was observed in the summer surveys (Vavrinec 2003, Steneck unpublished). Standing urchin biomass was low relative to the Schoodic and Pemaquid regions. Harvesting impacts were not dramatically evident at the control sites, nor did protection from harvesting at the MPA's result in gains in biomass.

Possible Causes of MPA Failure

Vavrinec (2003) reviewed the range of reasons MPA's have failed to achieve their objectives in other locations around the world, and weighed the evidence for them as explanations for cases where the Maine sea urchin MPA's failed to meet their objectives. They include poor site placement, pollution, poor recruitment potential, slow growth, Allee effects, poor enforcement and compliance, and the development of unexpected trophic cascades. To summarize briefly, neither poor site placement nor pollution were considered to be factors here since all the sites had supported large urchin populations at one time, and there was no evidence

of pollution. Poor enforcement may have been a factor at the Schoodic MPA where poachers had been seen, but this was not likely a problem at the other sites.

Slow growth may have been a factor at any of the sites because the green sea urchin is a relatively slow-growing species, and four years may have been a relatively short time to expect an increase in collective biomass from growth, particularly if any biomass gains from growth were offset by mortality. For example, it is worth noting that although there was a gain in biomass at 5 m at the Pemaquid MPA during the study, the drop in the proportion of legal urchins from 2002 to 2003 may explain the decline in overall biomass at that depth.

Low recruitment potential may have been a factor in the eastern Maine MPA's (Jonesport and Schoodic) where larval settlement is extremely low for oceanographic reasons, despite the presence of intact breeding populations there (Harris 1996, McNaught and Steneck 1999). Ironically the York region, where breeding urchins have been all but exterminated, continues to receive a plentiful larval supply, so recruitment potential there remains high. In York the development of a trophic cascade is more likely to have determined the failure of the MPA's. That is, depleting sea urchins, the primary consumer of macroalgae, has resulted in a switch in the benthic community from an urchin dominated "barrens" to a habitat dominated by fleshy kelp and foliose red algae. This alternate habitat is inhospitable to larval settlement because of high densities of resident predators that are able to consume small juvenile urchins, such as small crabs and polychaetes (McNaught and Steneck 1999). Moreover, this community state appears to be relatively stable and resistant to reversal. Attempts to return the community to urchin barrens through removal of algae and transplantation of mature sea urchins has not been successful to date (Leland 2002).

Allee effects, in the form of diminished per-capita reproductive success at low density were dismissed in the Vavrinec (2003) report as not likely to play a role in the failure of the MPA's. However, Allee effects, as currently defined, involve more than density-dependence of per-capita reproductive output (Stephen et al. 1999, Peterson and Levitan 2001). The poor juvenile recruitment resulting from the trophic cascade may in itself be regarded as an Allee effect because it is a result, albeit indirect, of declining adult densities. The impact of Allee effects in the recruitment process remains poorly understood in sea urchin population dynamics and requires further research.

Finally, the small scale of the MPA's in this study may have also contributed to their failure. Most other examples of successful MPA's cited above have been orders of magnitude larger in area. The smaller the population, the more vulnerable it is to extinction by local disturbances, natural or anthropogenic. For example, a single poaching event (e.g., Schoodic MPA) can have a much greater proportional impact on a small population than a large one. Also, because the perimeter-to-area ratio is greater the smaller the area, edge effects also become increasingly important, where mortality processes operating outside the MPA may reach within.

Density- and Depth-dependence of Reproductive Output

The winter surveys of the MPA and control sites have added further insight into the responsiveness of roe yield to changes in population density. The density- and depth-dependence of algal cover and gonad index observed here were consistent with prior reports (Keats et al. 1984, Wahle and Peckham 1999). Gonad yield per square meter scaled linearly with sea urchin biomass over the range of sea urchin biomass observed in this study (up to 2500 g per m²). Although individual gonad mass as a percent of body mass declined significantly with

increasing urchin biomass and depth, most likely as a result of food limitation, there is no evidence that within the range of urchin biomass observed in this study that collective gonad yield of the population per unit area reached asymptotic levels. This is consistent with previous studies even where population biomass was as high as 6500 g per m² (Wahle and Peckham 1999). The implication is that the even the most densely populated MPA's have a greater capacity to support higher populations and roe yield.

Prior research suggests that the reproductive costs to sea urchins of living at high density are far less than the benefits (Wahle and Peckham 1999). Because losses in individual gonad mass are small relative to the gains in fertilization success found among closely spaced urchins, the green sea urchin appears to be able to live in very dense aggregations and still successfully reproduce. Thus while individual gonad indices may be low under conditions of food limitation at high density or at greater depth, the reproductive potential of these populations may be quite high. Moreover, recent field experiments indicate sea urchins living in large, dense aggregations are more likely to spawn and have high fertilization rates than urchins in small isolated aggregations (Gaudette 2004).

Thus, although urchins in dense populations with low gonad mass may be of less economic value to the harvester, the potential benefits of their reproductive output should not be underestimated. The contribution of this reproductive effort to the fishery would depend on the size of the population protected and the extent to which their offspring recruit to exploitable populations or are exported beyond them. Quantifying that contribution remains a challenge, however.

Is there a Future for Sea Urchin Marine Protected Areas in Maine?

If we are to take any lessons from the sea urchin MPA effort in Maine, it should not be that the MPA's were a failure, or that MPA's do not continue to offer a solution to the recovery of Maine's sea urchin fishery. Several positive aspects of our results may bode well for the application of MPA's to the Maine sea urchin fishery. First, some areas did show gains or at least stemmed declines seen in areas that continued to be subject to harvesting. In these cases, resident urchins had the opportunity to reproduce and contribute to the local and downstream larval supply that they otherwise might not have had. In the meantime we have refined our understanding of the density- and depth-dependence of algal cover and roe yield. Moreover, through long term, multi-site monitoring of these areas we have come to understand that depleting urchins below certain density thresholds causes a shift to an alternative community state through a trophic cascade in which urchin barrens are converted to kelp beds with negative consequences for future recruitment (McNaught and Steneck 1999, Vavrinec 2003).

As the science of marine reserves becomes an increasingly active research arena in marine ecology and fisheries, several challenges lie ahead. First, if we are to give MPA's a more comprehensive critical evaluation in Maine, it will be important to evaluate the relative gains that might be realized from closed areas as compared to traditional fisheries management options, such as size limits, effort reduction, or quotas. Model simulations that make such comparison suggest that marine reserves stand to be most beneficial to relatively sedentary taxa such as sea urchins and scallops as compared to wide-ranging species, such as finfish (Gerber et al. 2003). Several red sea urchin (*S. franciscanus*) fisheries on the west coast are contemplating or have begun to practice rotational closures in combination with standard management practices (Andrew et al. 2002); it will be important for sea urchin managers to track their success.

A second challenge is to determine the size and number of reserves necessary to have the desired effect both within and outside their boundaries (e.g., Botsford et al. 2003). For lack of empirical data that can take many years to collect, recent modeling approaches have been helpful in determining the costs and benefits of different strategies and configurations (Airame et al. 2003, Leslie et al. 2003, Shanks et al. 2003). A rule of thumb emerging from a review of a number of fisheries suggest that somewhere on the order of 25-40% of the fishable area should be protected to ensure sustainability (Roberts et al. 2001). Optimizing the configuration into a few large or many small areas would depend on the objectives and regional geography. Whether the 25-40% rule of thumb applies to the green sea urchin in Maine remains an open question.

As research continues to evaluate the cost and benefits of protected areas for the Maine sea urchin, two types of benefits should be born in mind – those within the protected area and those outside. In the case of the green sea urchin, the benefits within the reserve are relatively easy to measure, such as increases in density, gains in body size, and maintenance of habitat hospitable for larval settlement. Benefits outside the reserve fall into two categories: (1) “spillover”, the movement of juveniles and adults outside the boundaries of the reserve, and (2) export, the dispersal and advection of water borne larvae to the outside. Because urchins are relatively sedentary or slow moving, spillover is likely to be very limited. Measuring the contribution by larval export and settlement elsewhere remains a significant challenge, but one of prime importance in view of the potential dependence of one segment of the coast on larval supply from another.

Circulation modeling has been helpful in indicating probable larval sources and sinks in the Gulf of Maine (e.g., Xue et al. 2000), and will be helpful in suggesting where to situate conservation areas. Because of the strong east to west directionality of long-shore currents along

the Maine coast it will be especially important to protect and assess the potential contribution of populations in the east to the larval supply in the west. Indeed, the best hope for recovery in western Maine may be the remaining urchins in the east. As an example from another New England fishery, scallop grounds closures on Georges Bank have significantly enhanced larval subsidies to surrounding areas (Murawski et al. 2001). The positive effects of rotational closure as a compromise strategy would be two-fold: It would allow recruitment by growth into legal sizes for several years within the close area, and the opportunity for mature urchins to breed beyond the legal size that they otherwise would not have had.

Conclusions & Recommendations

This report summarizes the results of winter surveys conducted to evaluate changes in sea urchin biomass, roe yield, and algal cover at 5 and 10 m depth at each site over a four-year period. Results of summer surveys through 2002 assessing urchin biomass, algal cover, and larval settlement are reported in Vavrinec (2003); an update including the 2003 summer survey will be available in a subsequent report.

The outcome of protecting sites from sea urchin harvesting varied by site. At the Pemaquid Point MPA we observed increases in urchin biomass and roe yield per unit area, whereas at the control site nearby, where harvesting continued, biomass declined precipitously and the benthic community shifted from urchin dominated “barrens” to kelp beds. In this case, the closure clearly pre-empted harvesting depletion. In contrast, at the two MPA’s established in the York region, the sea urchin population had already been severely depleted several years earlier (Vavrinec 2003). No urchins were found at these sites; they were entirely dominated by fleshy macroalgae, and we saw no recovery of the urchin population during the course of the

study. At the Schoodic Point MPA, contrary to expectation, sea urchins declined more rapidly within the MPA than at the control site, and eye witness accounts indicate poaching had been at least partly responsible. In the Jonesport region sea urchin biomass was already at low levels when the MPA's were established, but there was little change in biomass at any of the sites over the course of the study.

Gonad indices (roe weight as a percent of body weight) were inversely related to population density and depth. This is likely a result of food limitation as algal cover also declined significantly with density and depth. In spite of the loss of individual gonad mass at greater densities, we observed a linear increase in roe yield per unit area of seabed with increasing adult densities. The absence of an asymptotic relationship over the observed range of adult biomass suggests there is a potential for greater reproductive output at even the high density sites.

Together with previous findings our results suggest that MPA's may hold some promise as a management tool for the Maine sea urchin fishery. However, it will be necessary to weigh the benefits to be realized through MPA's as compared to traditional management strategies. Specifically, research is required to better understand the impact of MPA size and configuration on yield both inside and outside its boundaries. Furthermore, because of the dramatic impact that changes in population density can have on reproductive performance, community state, and subsequent recruitment, research continues to be necessary to understand population dynamics of depleted populations, particularly with respect to (1) the reproductive consequences of living at low density or in small aggregations, and (2) the mechanisms facilitating the reestablishment of urchin populations where the benthic community has reverted to kelp beds.

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Table 1. Names and positions of Maine’s sea urchin marine protected areas and corresponding control sites. Winter surveys were conducted from 2000 to 2003.

Region	MPA	Control
York	East Point N 43° 8.0’ W 70° 37.2’	Cow Beach N 43° 8.4’ W 70° 37.2’
York	Seal Head Point N 43° 7.2’ W 70° 37.9’	Stone’s Rock N 43° 6.5’ W 70° 38.4’
Pemaquid	Pemaquid Point N 43° 50.1’ W 69° 31.0’	Thrumcap Island N 43° 49.0’ W 69° 33.1’
Schoodic	Schoodic Peninsula N 44° 20.4’ W 68° 02.5’	Little Moose Island N 44° 20.0’ W 68° 02.6’
Jonesport	Outer Ram Island N 44° 29.5’ W 67° 38.2’	Ram Island N 44° 29.5’ W 67° 38.1’
Jonesport	Sea Duck Rock N 44° 29.1’ W 67° 39.2’	Little Drisko Island N 44° 29.0’ W 67° 39.8’

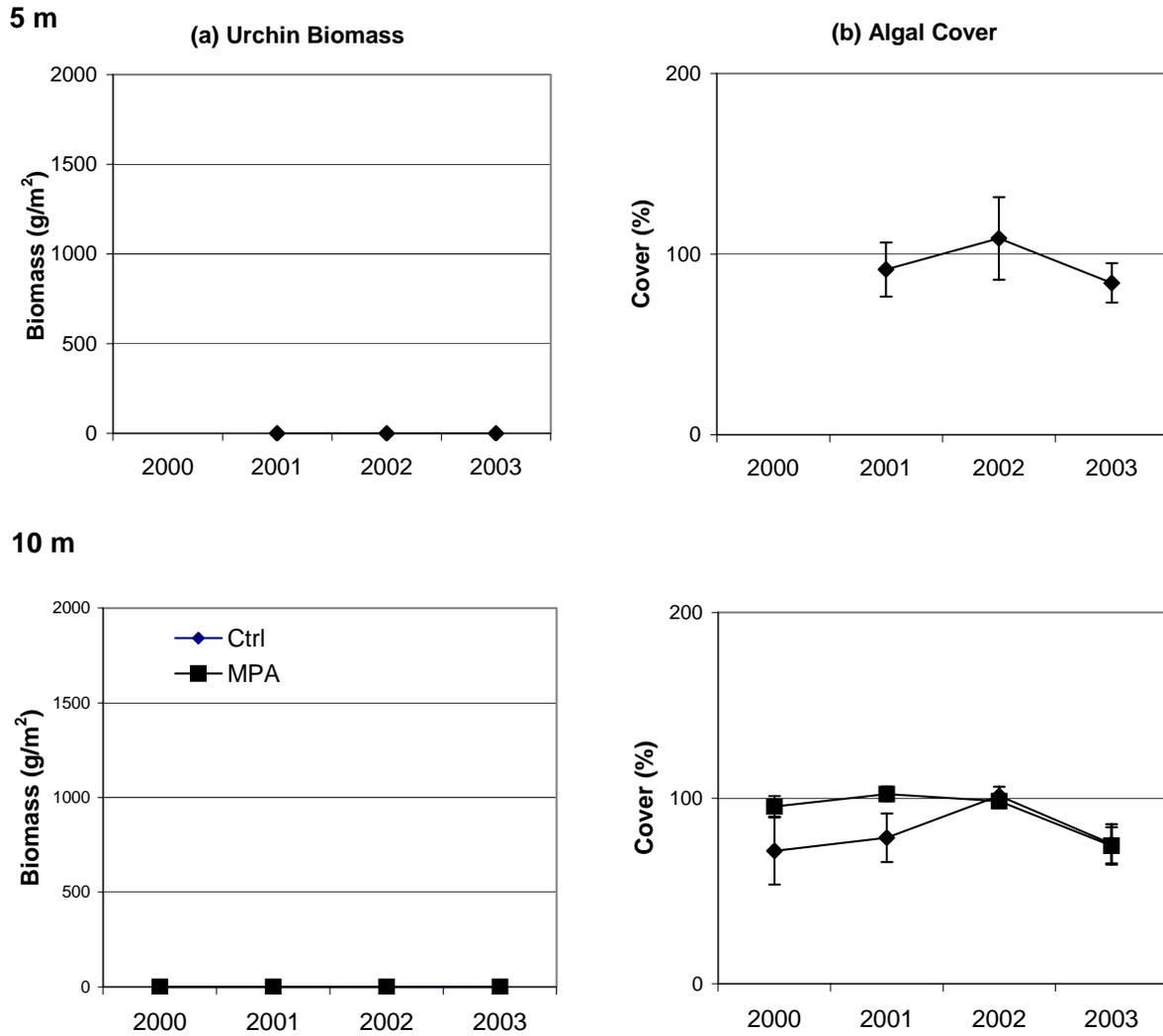


Figure 1. York (East Point MPA and Cow Beach Control). Mean (+95% CI) sea urchin biomass (a), and algal cover (b) at 5 and 10 m depth. Surveys at 5 m depth were only conducted at the Control site.

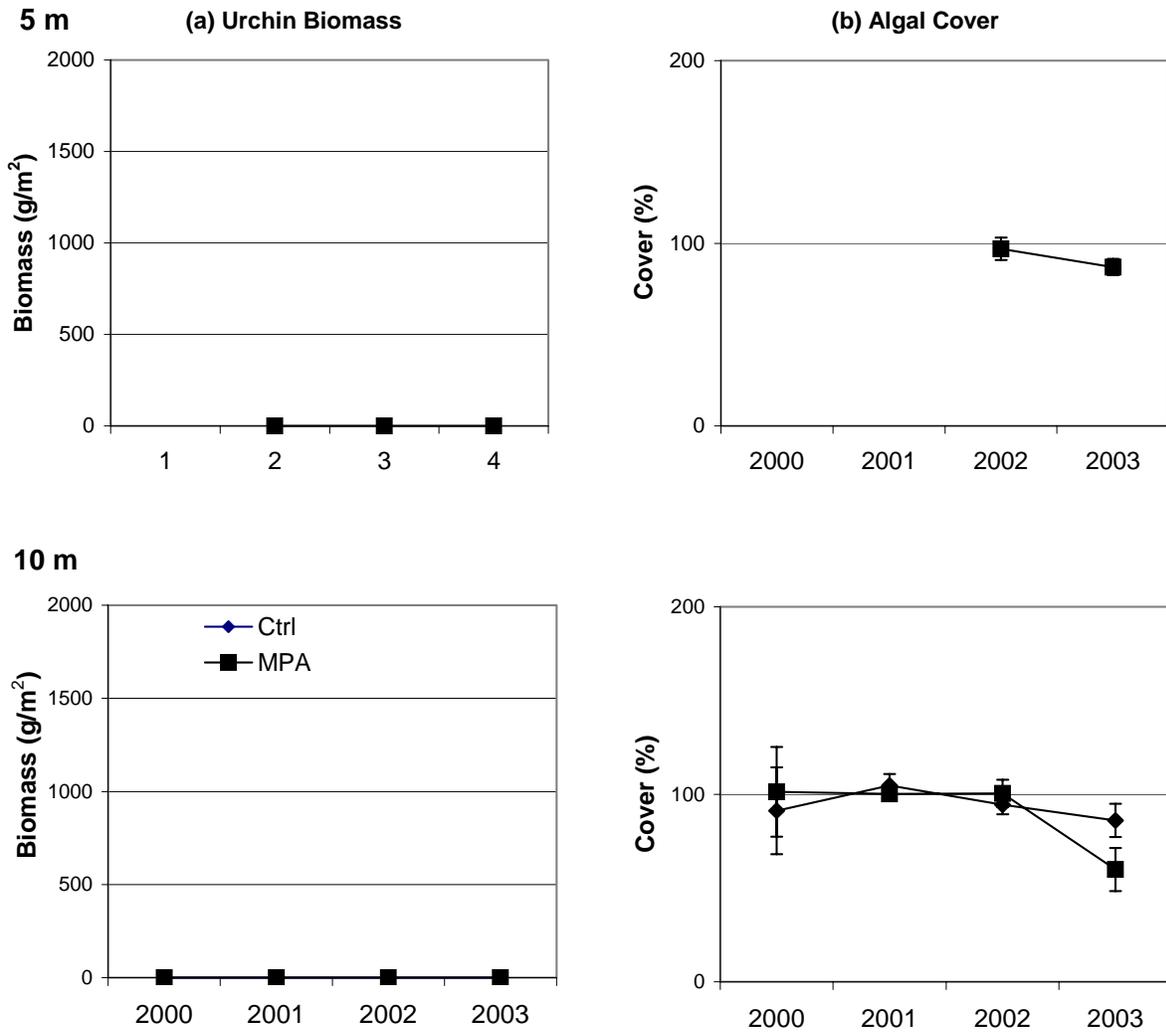


Figure 2. York (Seal Head MPA and Stone's Rock Control). Mean (+95% CI) sea urchin biomass (a) and algal cover (b) at 5 and 10 m depth. Surveys at 5 m depth were only conducted at the MPA site.

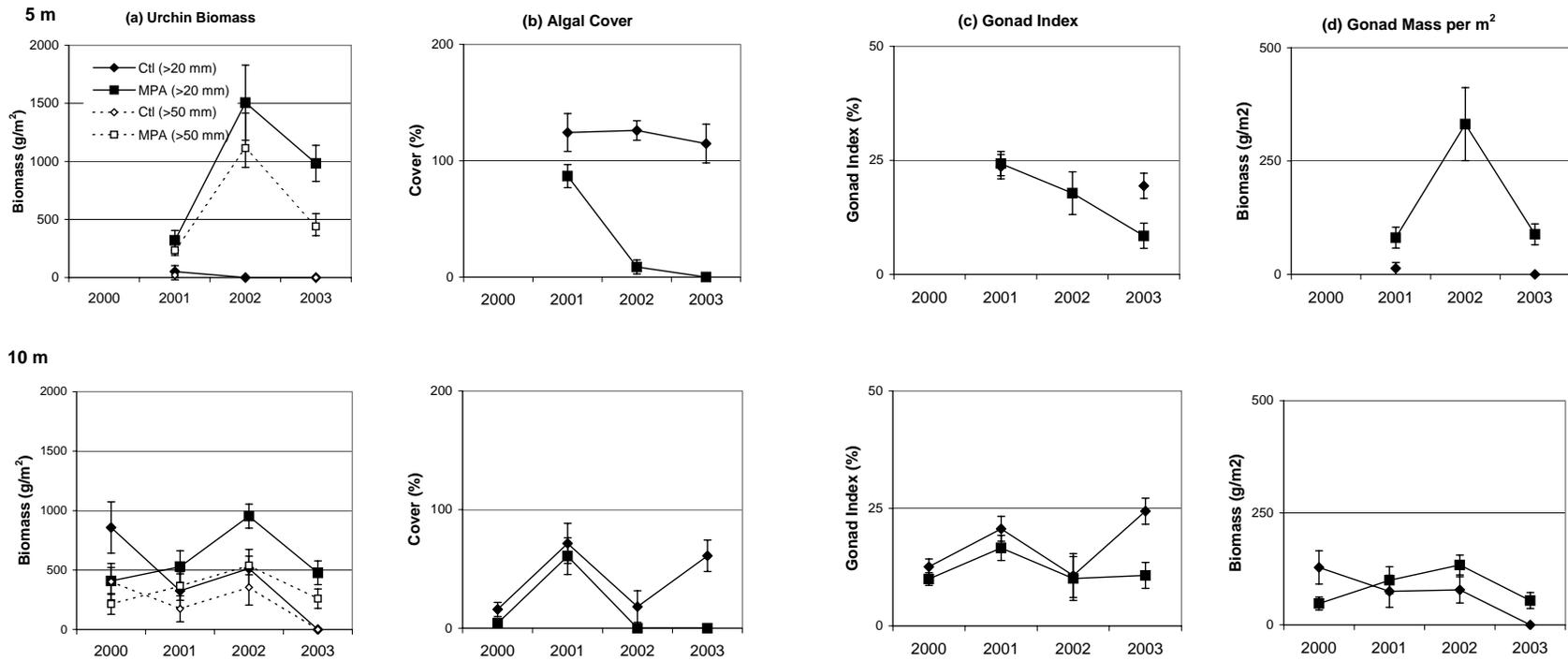


Figure 3. Pemaquid Point (Pemaquid Point MPA and Thrumcap Island Control). Mean (+95% CI) sea urchin biomass (a), algal cover (b), gonad index (c), and gonad mass per area (d) at 5 and 10 m depth.

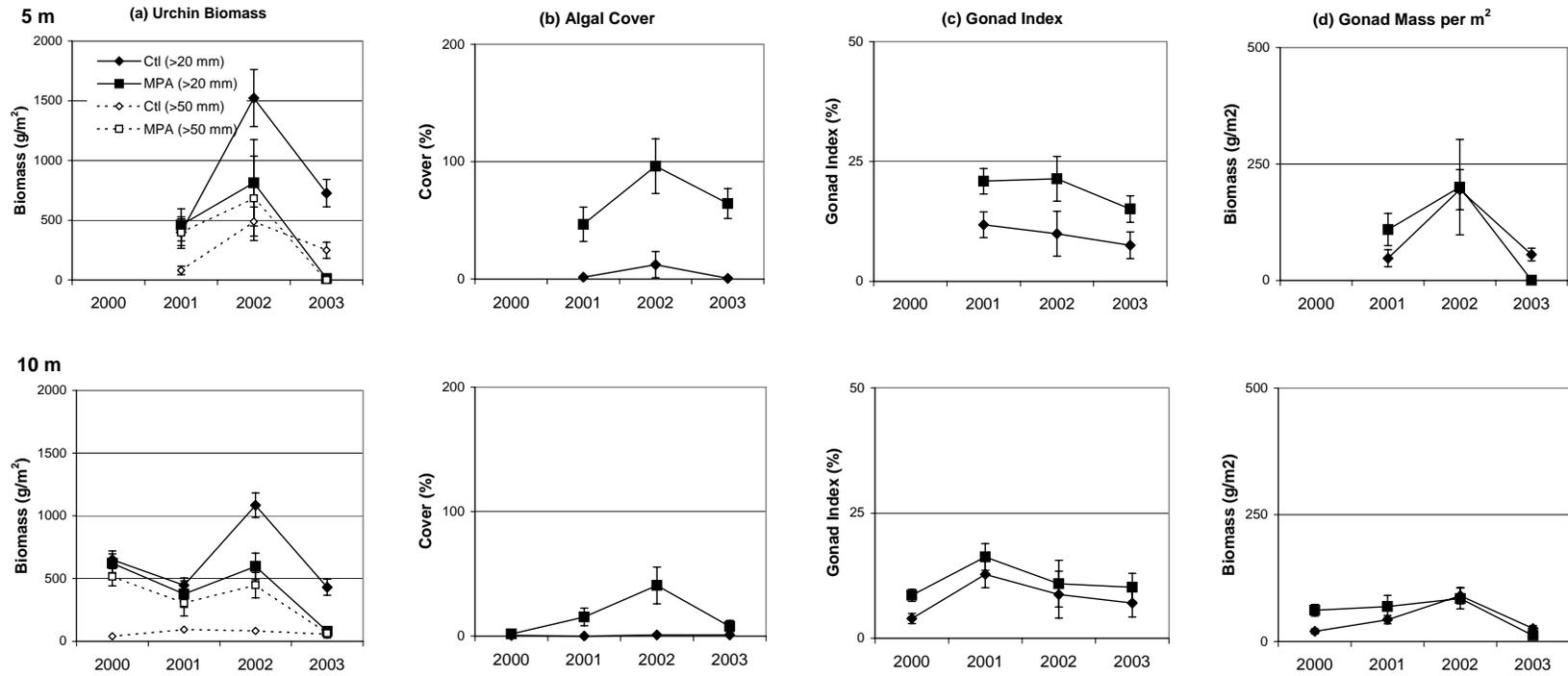


Figure 4. Schoodic Point (Schoodic Point MPA and Moose Island Control). Mean (+95% CI) sea urchin biomass (a), algal cover (b), gonad index (c), and gonad mass per area (d) at 5 and 10 m depth.

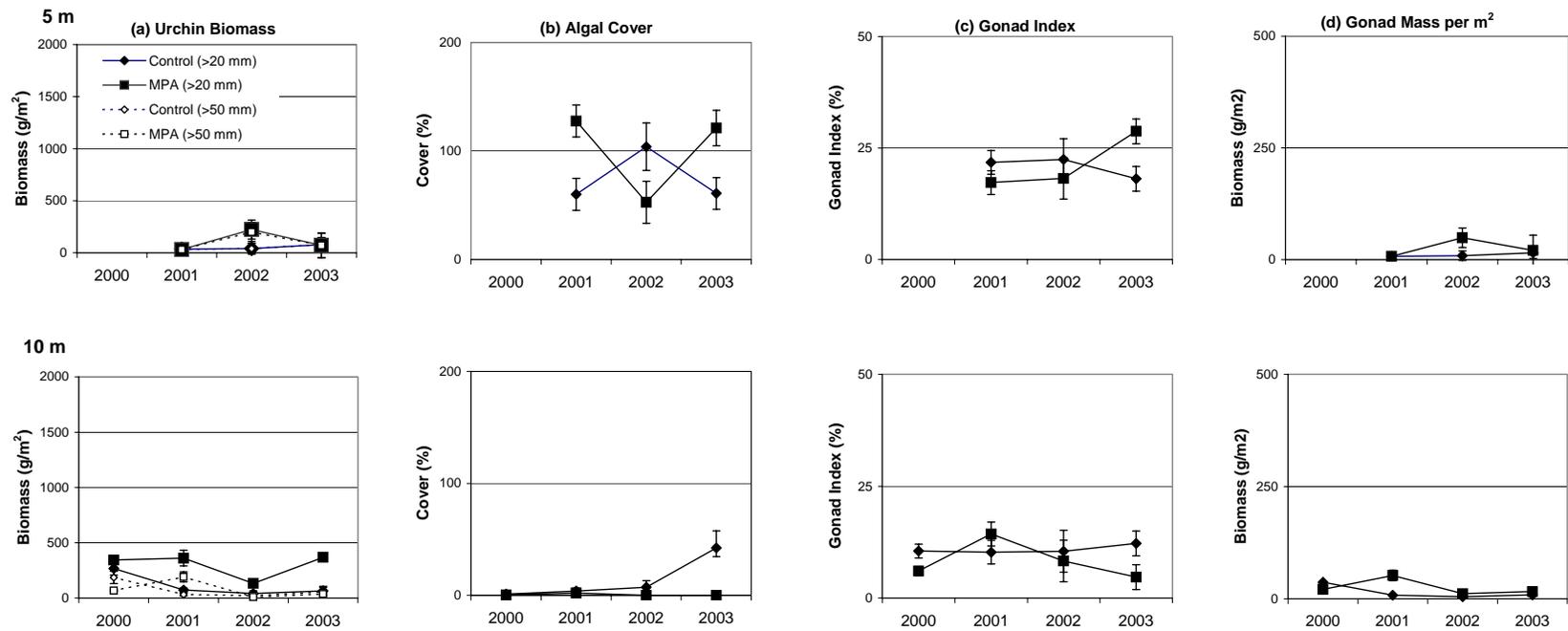


Figure 5. Jonesport (Ram Island MPA and Ram Island Control). Mean (+95% CI) sea urchin biomass (a), algal cover (b), gonad index (c), and gonad mass per area (d), at 5 and 10 m depth.

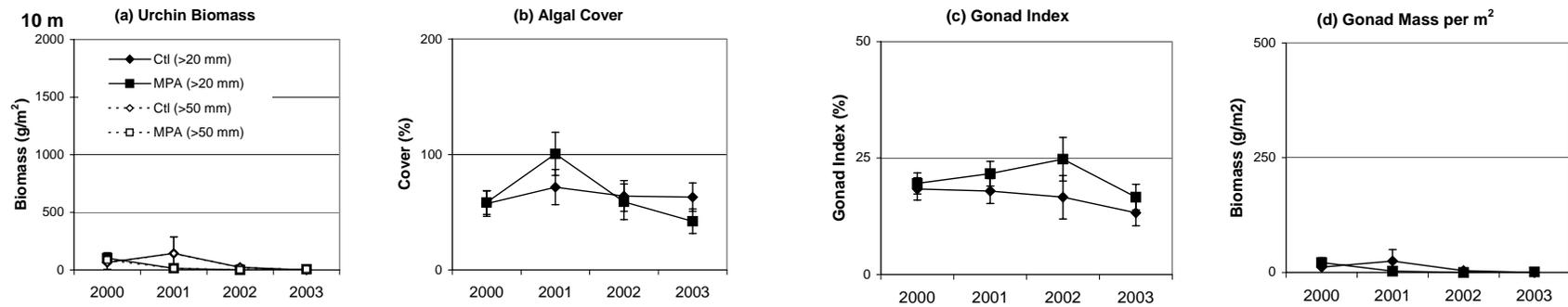


Figure 6. Jonesport (Sea Duck Island MPA and Little Drisko Island Control). Mean (+95% CI) sea urchin biomass (a), algal cover (b), gonad index (c), and gonad mass per area (d), at 10 m depth.

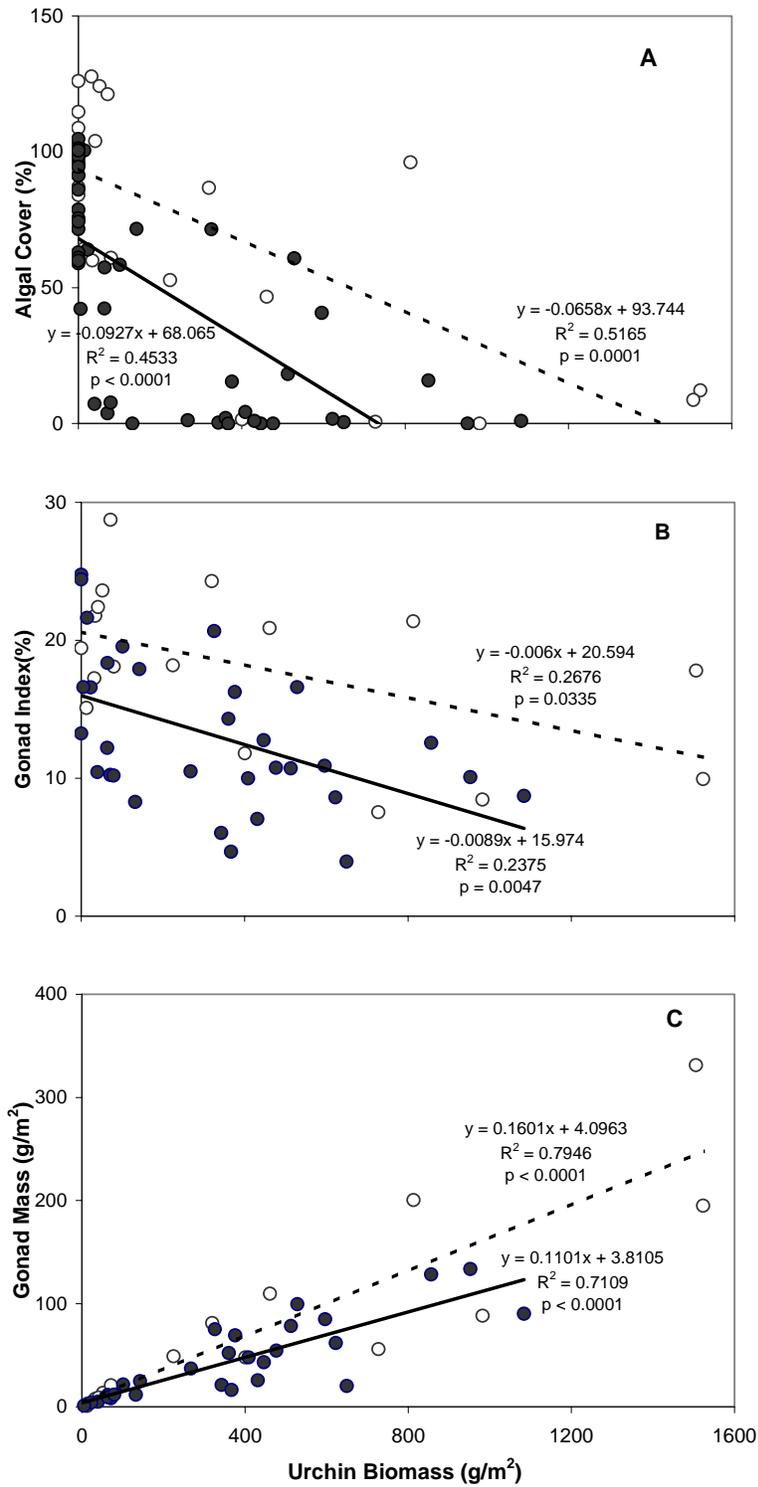


Figure 7. Regression analysis for the relationship between biomass of sea urchins >20 mm and (a) algal cover, (b) gonad index, and (c) gonad mass per m² at depths of 5 m (open circles, dashed line) and 10 m (closed circles, solid line).

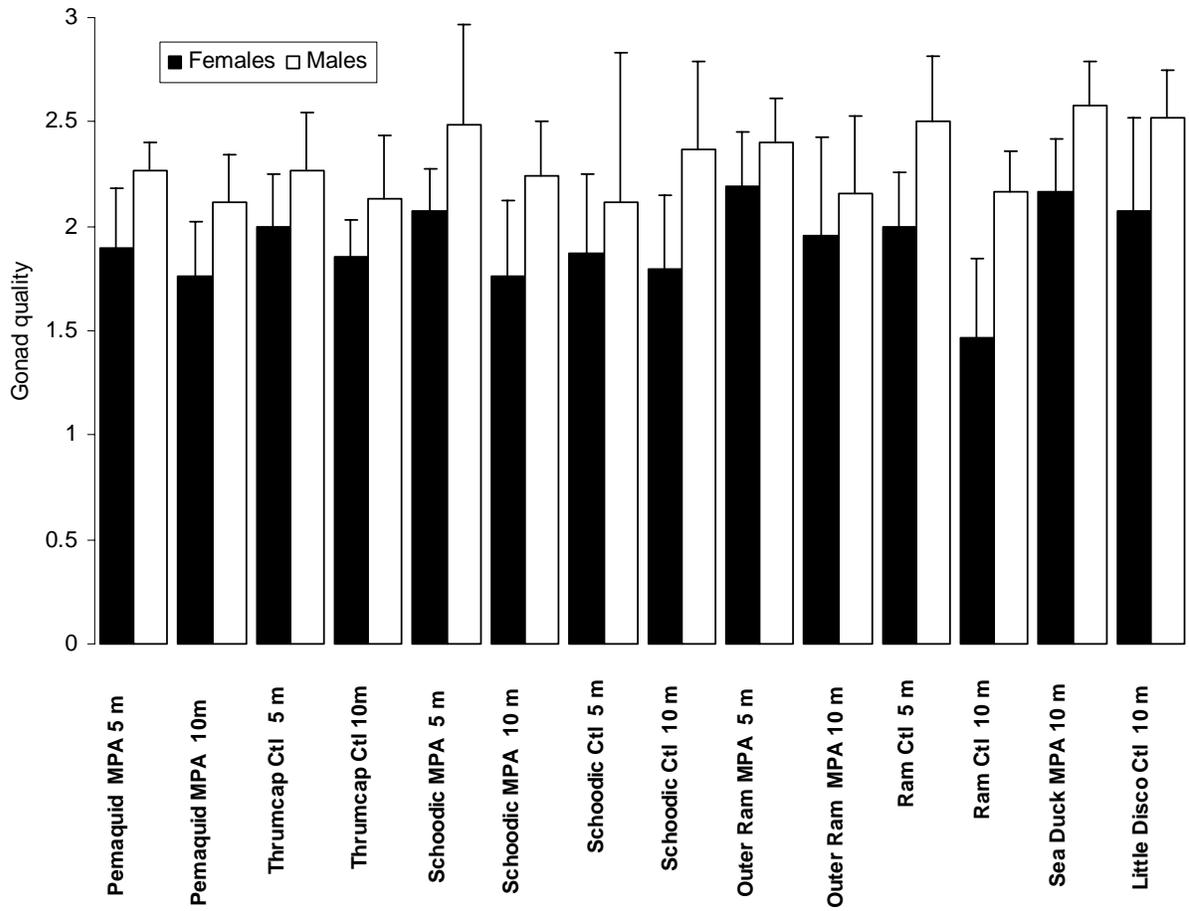


Figure 8. Roe quality index for male and female urchins collected at 5 m (shallow) and 10 m (deep) from eight study sites. Sea Duck and Little Drisco sites were only sampled at 10 m.