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Marine Protected Areas and the Early Life History of Fishes

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Abstract

With the shortcomings of other fisheries management schemes, creating no-take marine reserves or Marine Protected Areas (MPAs) is increasingly gaining support. MPAs have already been established in several places around the world. MPAs are generally associated with tropical or temperate reefs, in areas where reef-associated populations have been severely overharvested. One justification for MPAs is that fish in the reserves grow larger, become more fecund, and thereby locally increase larval supply. It is reasoned that through egg or larval transport some of the larvae will settle elsewhere and thus will enhance juvenile recruitment over an area much larger than the reserve itself (the "seeding effect"). Theoretical studies have demonstrated this effect of MPAs, but field work is generally lacking. The present paper examines some of the assumptions of the theoretical studies including the increase in larval production that would be required to be detected by larval surveys. The importance of habitat requirements of larval, juvenile and adult life stages and the general disconnect between larval production and recruitment in marine fishes are discussed relative to arguments for MPAs. The anticipated increase in larval production of copper rockfish, *Sebastes caurinus*, resulting from implementation of MPAs in the San Juan Island area of Washington State is simulated, and the question of whether this increase can be detected by plankton sampling is addressed. A model of the currents in the area was used to simulate dispersal of larvae from the MPAs, and a simulated larval sampling program demonstrated that the increase in larval production once the reserves were operational could be detected.

Contents

Introduction

Fisheries Mismanagement

The 20th century was marked by increased exploitation of living marine resources, and parallel increases in our attempts to manage these resources for long-term sustainability. We went from considering the ocean's resources as unlimited, and available for unbridled exploitation, to trying to manage fisheries. In spite of these management efforts, widespread overfishing occurred. With the widespread depletion of fish stocks, a call has gone out for conservation and restoration of the resources of the ocean, with some even calling for preservation measures, as is the case with marine mammals.

Recently we have become increasingly aware of the impact of overharvest on living marine resources. Whether it is tropical reefs and their community of fishes being decimated for the aquarium trade, or the collapse of large-scale industrial fisheries such as the Northwest Atlantic cod (*Gadus morhua*) fishery, even the general public has become aware of serious problems throughout the marine ecosystems (Agardy 1999).

Besides limiting harvest to stabilize fished populations, various attempts have been made to enhance them, through hatcheries at first, and now though setting aside marine protected areas (MPAs). Now we are looking for new ways to prevent further damage to marine ecosystems, and ways to restore populations to their former states. There is a basic change in philosophy toward a precautionary approach in fisheries management (Lauck et al. 1998), and protecting part of the habitat to enable stocks to rebuild is gaining considerable support. Some are even suggesting a basic reversal in thinking: MPAs should be the rule and fishing areas the exception (Walters 2000).

A Partial Solution: MPAs

With the shortcomings of other fisheries management schemes, creating no-take MPAs is increasingly gaining support, and such have already been established in several places around the world. In the United States, for example, to date the Marine Protected Areas Federal Advisory Committee has identified 328 marine managed areas. These are primarily federal sites under jurisdiction of NOAA or the Department of the Interior. There are some federal/state partnership sites, sites in two states (Maine and Massachusetts), and in one territory (Commonwealth of the Northern Marianas Islands). MPAs have been established in both tropical and temperate areas. Many are located in tropical coral reefs around the world, to protect this type of habitat as well as to rebuild the communities associated with it. In temperate areas, MPAs have been established offshore over hard and soft bottom env~~o~~ironments. The closure of large areas of Georges Bank to fishing in 1994 had dramatic effects on the populations of scallops as well as several species of harvested fishes (Murawski et al. 2000). The areas around the California Channel Islands have been a marine sanctuary since 1980, but in response to severe declines in local rockfish (*Sebastes* spp.) populations, MPAs were established there in 2003 (http://www.csc.noaa.gov/cms/MPALessonsLearned.pdf [11 September 2003]). An early example of a temperate, nearshore MPA, the Edmonds Underwater Park in Puget Sound, Washington, was established in 1970 as an artificial reef that was closed to fishing so scuba divers could enjoy observing the community of large fishes that took up residence there (Palsson 1998).

Even though a few marine areas have been excluded from harvest for some time, this practice has recently become more widely accepted as a means to reverse the downward trend in abundance of fishes and other marine life worldwide. Also, with the destruction of essential fish habitat by fishing practices (e.g., Koenig et al. 2000), there are calls for setting aside areas for re-establishment of unperturbed marine ecosystems, for conservation and enhancement of marine resources and to allow study and casual observation (Agardy 1999). In the United States Executive Order 13158 designed to strengthen the protection of coastal and ocean resources through MPAs was signed in May 2000.

Several objectives have been cited for establishing MPAs (Dugan and Davis 1993a, Jones 1994). The potential effects of MPAs on target populations include: increased abundance, increased individual size and age (Roberts 1995), increased reproductive output, enhancement of nearby populations (Auster and Shackell 2000), enhanced recruitment inside and outside the reserve (Dugan and Davis 1993b), increased resilience to overharvest (Guenette et al. 1998), and increased protection against recruitment failures. Potential community benefits include: increased species diversity (Western 1995), increased habitat complexity, increased community stability (Dugan and Davis 1993b), restoration of ecosystems to preharvest structure (Babcock et al. 1999), and development of unspoiled areas for viewing fish and associated life (ecotourism).

Enhancing nearby populations is the most compelling aspect of MPAs for fishers and fisheries managers, although the effectiveness of this function is still under debate (Conover et al. 2000). Enhancement can occur by two means: spillover of juveniles and adult emigrants from the reserve to nearby areas, and transport of eggs and larvae produced in the reserve to fished areas (the "seeding effect"). Spillover of adults has been documented in some cases (e.g., Russ and Alcala 1996, Roberts et al. 2001), but the recruitment, "seeding effect" is largely conceptual and has mainly been the subject of modeling studies (e.g., Dight 1995, Guenette et al. 1998, Stockhausen et al. 2000, Botsford et al. 2001). The enhancement value results from recruits that originated from eggs and larvae produced by the larger more fecund adults in the reserve dispersing to fished areas and settling and recruiting there (see Man et al. 1995).

Of course not all fish are suitable candidates for protection by MPAs. Most reserves are designed for rather sedentary fish that live in association with bottom structure; for example, coral reefs or temperate rocky-reefs. Fishes with restricted movements and localized home ranges during at least part of their life cycle will benefit most from reserves (Kramer and Chapman 1999). Long-lived fish will benefit from this protection by continuing to grow and increase in fecundity (Davis 1989). A reproductive pattern that includes a relatively long dispersal period, as eggs or larvae or both, is required to increase recruitment in adjacent areas. Consideration of other life history strategies, such as sequential hermaphroditism, and spawning migrations and aggregations should be included when planning MPAs. Clearly, an understanding of the species to be protected is needed to decide if reserves will be effective, where they should be located, how large they should be, and how many there should be (c.f. Lindeman et al. 2000). For example, Martell et al. (2000) found that life history characteristics of lingcod (*Ophiodon elongatus*) which include seasonal spawning migrations necessitate reserves being large and permanent.

MPAs are presently one of the most active topics in marine science. There is a rapidly growing body of literature on them (see Appendix), several websites exist (e.g., http://www.panda.org/resources/publications/water/mpreserves/ma_dwnld.htm [11 September 2003]), and several conferences have been held recently (e.g., Dugan and Davis 1993a, Yoklavich 1998, Conover et al. 2000, NRC 2001).

The Track Record of MPAs

In a review of MPAs in Canada, Jamieson and Levings (2001) found that the term has not been rigorously defined, and in some cases little or no protection of fishes from harvest actually occurs in these areas. Thus, the objectives and regulations associated with MPAs need to be clearly stated for them to be effective.

Halpern and Warner (2002) reviewed empirical studies on 80 MPAs and found rapid and lasting effects of protection from harvest demonstrated by increases in abundance, size and diversity of fishes within the reserves; effects on populations outside the reserves were not reviewed. Cote et al. (2001) examined the effects of MPAs on diversity and abundance of fishes, and found that species richness was consistently greater in the reserves, but abundance was greater only for those species that were subject to nearby fishing pressure. Jennings (2000) modeled the recovery of fish populations that were protected from harvest in MPAs and found that with small areas, it might not be possible to distinguish between redistribution and population growth. He did not address the possible benefits that might accrue due to increased recruitment.

MPAs and Recruitment

One of the primary objectives of MPAs is to increase recruitment of target species both within the reserves and in adjacent areas (Fig. 1). More fish will then be available for harvest in these adjacent areas that are open to fishing. The idea is that adults in MPAs which are free from harvest will live longer and grow larger. Since fecundity is directly related to fish size, roughly to length cubed, the larger fish will produce many more eggs. In most marine fish the eggs are planktonic and along with the larvae are the primary dispersal phases in sedentary fishes. Thus the eggs and larvae produced in the MPA will settle in the reserve and in adjacent areas to enhance recruitment both within the reserve and elsewhere (Carr and Reed 1993). However, in a review of 31 empirical studies on the effects of MPAs on target populations (both finfish and invertebrates), Dugan and Davis (1993b) found only three that considered recruitment effects: one of these showed positive effects and two did not demonstrate any effect. More recently Planes et al. (2000) "found an exceptionally low number of studies specifically addressing recruitment processes in MPAs". Stoner and Ray (1996) conducted one of the few studies to date examining the effects of an MPA on larval production. Abundance of queen conch, *Strombus gigas*, larvae appeared to be directly associated with increased abundance of adults in the MPA. Enhanced recruitment in the reserve was thought to be due to arrival of settling-competent larvae from upstream areas outside the reserve. Contributions of larvae produced in the reserve to nearby fished areas was not demonstrated.

In order for recruitment enhancement to occur, the fished area must be within the dispersal distance of the eggs and larvae produced in the MPA (Guenette et al. 1998, Botsford et al. 2001). However, little is known about dispersal of larvae and while some probably travel long distances others seem to be retained near the area where they were produced (Swearer et al. 1999, Warner et al. 2000). For a reserve to act as a source for recruits to a fished area, prevailing currents must carry the eggs and larvae toward the fished area (c.f . Dahlgren et al. 2001). If currents run from the fished area to the reserve, the area could be considered a sink rather than a source of recruits, and would not enhance recruitment in the fished area (Roberts 1998, Crowder et al. 2000). Valles et al. (2001) found that larval supply was greater over a fished area than over a nearby MPA, pointing out the need to carefully site reserves so they provide adequate larval supply for enhanced larval settlement and eventual recruitment. Since little is known about larval dispersal, networks of reserves which will act as sources of larvae are recommended (Roberts et al. 2001).

Another consideration regarding the enhanced recruitment value of MPAs is that the juveniles may not settle directly onto the habitat occupied by the adults. For example, if larvaae or juveniles settle onto soft bottom environments, or in vegetation and move to the reefs later, these discrete juvenile habitats may need to be protected to allow for the conservation and enhancement of the target species (c.f. Hill and Creswell 1998). Lindholm et al. (2001) found that habitat change caused by trawling and dredging resulted in increased predation on juvenile Atlantic cod, and suggested that excluding some juvenile habitat from fishing could ameliorate these effects. However, reserves in reef areas might have a negative effect on settled juveniles, if they are subjected to increased predation from the greater abundance of piscivorous adults in the reserves (Tupper and Juanes 1999, Garcia Rubies 1997 [cited in Planes et al. 2000]).

A Model of Fisheries Management Objectives of MPAs

A conceptual model of the effects of MPAs is shown in Figure 2. MPAs are supposed to conserve the marine life within their boundaries, and enhance it in nearby unprotected areas. The conservation role of reserves in recruitment is included in this diagram. Eggs produced by the larger, more fecund adults in the reserve result in more recruits that settle in the reserve. In fact, the population in the reserve could be increased by settlement of larvae produced elsewhere also. This benefit of the reserves assumes that the target populations are recruitment limited, and in fact that recruitment is limited by the number of offspring produced by the adult population (larval supply). If other factors are responsible for the reduced adult abundance in the area, the reserves may have little benefit.

MPAs in the San Juan Islands, Washington

The San Juan Islands are located in Puget Sound in northwest Washington and southern British Columbia (Fig. 3). The waters around the San Juan Islands are deep and have salinity and temperature characteristics close to those of the open ocean. The area is characterized by strong tidal currents. The main influence on net movement is the Frazer River which produces southward flow particularly during periods of high river discharge.

The San Juans Islands are rocky, and along their shores and in the channels between them is considerable habitat for temperate rocky-reef demersal fishes such as lingcod, greenlings, cabezon, and several rockfishes (*Sebastes* spp.). With the declines in abundance of Pacific salmon and associated fishing restrictions on them in Washington, sportfishers were encouraged to fish for "lowly" bottom fish, and they did so with a vengeance. These long-lived, sedentary species soon became overfished, and some have been proposed for listing under the Endangered Species Act. This prompted government agencies at every level and citizen's groups to seek ways to rebuild these stocks, and MPAs have surfaced as a way to accomplish this.

In response to declines in abundance of rocky-reef bottom fish, MPAs are being established in the San Juan Islands to enhance depleted populations of these species. These areas can be considered temperate water inshore MPAs. The San Juan Islands are in two counties in Washington: San Juan and Skagit. At present, MPAs are being established by these two counties through their Marine Resource Committees. San Juan County has established eight MPAs (Fig. 4), and Skagit County is now considering which of eight proposed sites to establish (Fig. 5). Within a year or so the Skagit County Marine Resource Committee will probably designate two to four of these as MPAs, and close them to all harvest. The counties have no formal jurisdiction over fishing in these areas, so compliance is voluntary. Washington's Department of Fish and Wildlife has several MPAs in other parts of the Puget Sound region, and may assume responsibility over these in the San Juans. With that would come mandatory compliance.

Copper Rockfish Recruitment and MPAs in the San Juan Islands

In order to look at these reserves in relation to recruitment of target species, we focussed on copper rockfish (*Sebastes caurinus*), one of the most abundant fished species in this area. We investigated the effects of establishing MPAs on output of larvae of copper rockfish: what would their dispersal patterns be, how would their numbers relate to the numbers of larvae produced by the present population, and could we expect to observe this change in numbers of larvae through ichthyoplankton sampling?

Life History Characteristics of Copper Rockfish (see Love et al. 2002)

These fish are long-lived (up to 50 years), and mature late (50% females mature at 6 years). The adults are quite sedentary, although they may move slightly when they release their larvae. Although they are viviparous they are highly fecund and release yolk-sac planktonic larvae. The larval phase lasts about 1-2 months, and the juveniles settle on kelp or soft bottom habitats and move to rocky areas with perennial macrophytes as they grow (Haldorson and Richards 1987). With these life history characteristics, copper rockfish seems a likely candidate for conservation and enhancement through MPAs. Its extreme longevity means that it would be several years before the results of establishing reserves might be realized.

Dispersal of Copper Rockfish Larvae

To investigate the potential dispersal of larvae of copper rockfish from the San Juan Islands reserves, we used models of the currents in the area (GNOME: General NOAA Oil

Modeling Environment and TAP: Trajectory Analysis Planner (Beegle-Krause 2001, Barker 1999)). The models we used were initially developed to track oil spills. Tides in this area range from about 3-4 m which generate strong currents and provide the main forcing for the model. For our use, we set the winds to zero to track the movement of the upper part of the water column where the larvae reside. A different tidal reference point was used for the Skagit County and San Juan County portions of the area, and results from running the model for each of these points were combined. The models were run 100 times over a 24-hour period between 15 April and 15 May to average over the effects of tides.

We know virtually nothing about the small-scale distribution of copper rockfish larvae or their behavior. For this modeling exercise, we assume that they reside in the upper part of the water column (< 20 m) and drift as passive particles. We realize that as the larvae develop they probably increase their ability to determine their own distribution, and might swim against the currents to be retained near the area where they were released; however, we treated the modeled larvae as passive particles. We planted 1,000 particles (larvae) at each of the 16 MPAs in the San Juans and let them drift passively with modeled currents (see Table 1).

Table 1. Parameters, assumptions and methods to simulate dispersal and the change in abundance of copper rockfish larvae in relation to MPAs in the San Juan Islands.

GRID

1. Define the area of interest, bounded on the west by the U.S./Canada boundary.
2. Compute the total surface area of water = 1,350 km^2.
3. Create a sampling grid by dividing the area into 2 km by 2 km grid cells, resulting in 359 grid cells.
4. Modify the cell boundaries to accommodate the coastline.
5. Place a sampling station in the center of each cell.

ADULTS

1. Estimated total number of adults = 2.141×10^6 (W. Palsson, pers. comm.).
2. We have not mapped copper rockfish habitat in the San Juan Islands, so we make the simplest assumption that adults outside of the MPAs are distributed uniformly. The consequence of this assumption on our analysis is to reduce sampling variability, however, our sampling simulation adds that variability back in by mimicking the variability from an actual survey.
3. Assume the population parameters of the copper rockfish outside the MPAs remain as they are now after MPAs are established.
4. Assume a 50:50 sex ratio (inside and outside reserves).
5. Assume the average length outside of MPAs is 30 cm.
6. Assume that MPAs are 10% of habitat (135 km^2).
7. Allocate 90% of the present population to outside of MPAs.
   $2.141 \times 10^6 \times 0.9 \times 0.5 =$ 963,450 females outside MPAs.
8. Allocate 10% of the present population to inside MPAs.
   $2.141 \times 10^6 \times 0.1 \times 0.5 =$ 107,050 females initially inside MPAs.

LARVAL PRODUCTION

1. Compute number of larvae per female outside the reserves, assuming 30 cm length, using two models and average their results:

Fecundity = $2.7404 \times 10^{-8} \times L^{4.9567} = 52{,}019$ (Washington et al. 1978)
Fecundity = $3.4554 \times 10^{-9} \times L^{5.30011} = 46{,}506$ (DeLacy et al. 1964)
Average Fecundity = (52,019 + 46,506)/2 = 49,263 larvae per female.

2. Compute number of larvae produced outside MPAs:

963,450 females × 49,263 larvae/female = 4.746×10^{10} larvae
which is equivalent to 4.746×10^{10} larvae / 1,215 km^2 = 3.906×10^{7} larvae/km^2.

3. Compute the number of larvae produced inside the MPAs: assume a 55-fold increase in larval production inside the MPAs (Palsson 1998). This is due to lower adult mortality inside the MPAs, which in time results in higher density of adults, and females are allowed to grow larger and hence produce more larvae per female. The MPAs are 10% of the total area (135 km^2):

Larvae produced inside the MPAs = $55 \times 3.906 \times 10^{7}$ larvae/km^2 $\times 135$ km^2 = 2.900×10^{11} larvae.

DISPERSAL OF LARVAE

1. Distribute the larvae produced outside of the MPAs evenly over the area, based on the assumption that the adults outside of the MPAs are distributed evenly.
2. Use the Trajectory Analysis Planner (TAP) program to predict distribution of larvae from MPAs 3 days after release.
3. TAP releases 1,000 particles (dots) at each MPA 100 times over a 24-hr period.
4. Each dot represents 2.900×10^{11} larvae / (16 MPAs × 1,000 dots/MPA × 100 start times) = 181,279 larvae/dot.
5. Count the number of dots within each sampling grid cell and convert to the number of larvae.
6. Compute the density of larvae in each grid cell by scaling the number of larvae to number per 10 m^2.
7. Create pairs of simulated populations 1,000 times. These two populations are:

7a. Background population - larvae produced outside of MPAs - each grid cell has the same density:

4.746×10^{10} larvae / (1,350 km^2 × (1,000 m/1 km)^2) = 351.45 larvae/10m^2

7b. Total population - each cell is computed separately - constant background population density plus density of larvae from TAP (i.e., the larvae from the MPAs) in that cell.

SURVEY SIMULATIONS

1. Reproduce the error structure of actual survey data. Lucie Weiss, U. Washington School of Fisheries and Aquatic Science, conducted an ichthyoplankton study in the waters around San Juan Island in spring 2002 and supplied us with her data on catches of rockfish larvae (pers. comm.). Simulate the error (ε_i) for each grid cell so that the distribution of ε_i looks like the distribution of errors from Weiss' data.
2. 51 out of Weiss' 103 observations are 0. Use binomial random variable with n=1 and p = 51/103 = 0.5 as one component of error. Generate a random series of "1" and "0".

3. For the 52 positive observations, estimate error using model $Y_i = \overline{Y} \times \varepsilon_i$ where Y_i is the observed density of larval rockfish in cell i, $\overline{Y}$ is the true mean density of larval rockfish, and ε_i is the multiplicative error term. Estimate the error as $\varepsilon_i = {Y_i}/{\hat{\overline{Y}}}$ where $\hat{\overline{Y}}$ is the average of the observed data.
4. Try different transformations of ε_i until their distribution looks like a standard probability distribution. The fourth root transformation looks normal. Estimate the parameters of normal distribution from the transformed errors.
5. Generate 359 (number of grid cells) random variables (ε_i) by multiplying the binomial random variable and the normal random variable.
6. Adjust the parameters of normal distribution until the coefficient of variation (CV) of the simulated errors is same as the CV of Weiss' data (using all of the data, not just positives) = 1.73.
7. Generate 359 new random variables (ε_i) by multiplying the binomial random variable and the normal random variable using the new parameters.
8. Generate a simulated survey of the background population by multiplying density in each cell (a constant value of 351.45 larvae/10 m^2, computed in Step 7a of Dispersal of Larvae section) by the 359 simulated errors.
9. Generate a simulated survey of the total population by multiplying the density in each cell (computed in Step 7b of Dispersal of Larvae section) by the same 359 simulated errors as used in Step 8.
10. Compute the mean of each simulated survey.
11. Repeat Steps 7-10 1,000 times.

COMPARISON OF SURVEYS OF BACKGROUND AND TOTAL POPULATIONS

1.Hypothesis test:
H_0: Mean density of total population is same as mean density of background population.
H_a: Mean density of total population is greater than mean density of background population.
Reject hypothesis if mean the density of survey of total population is greater than 95% of the mean densities of background population.
2. Plot the means of each simulated survey and compare the distribution of means from the background population surveys with the means from the total population surveys.

Initial conditions of "larvae" at each of the MPA sites in Skagit and San Juan Counties are shown in Figure 6. The same number of larvae were released from each of the 16 MPAs.

Figure 7 shows the distribution of the particles released at the MPA sites after 3 days of drift, the longest duration that the GNOME/TAP modelers feel comfortable with. During this period considerable numbers of larvae from the reserves in the western part of the area drifted out of the area to the west and southwest. Few larvae remained in the northwest part of the area, or near the west side of San Juan Island. High abundances of larvae were found between Orcas and Shaw Islands and to the west of Deception Pass. Few of the larvae that were released in Rosario Strait, or to the east drifted west of Rosario Strait. Larvae resulting from the reserves in Rosario Strait showed considerable mixing, and a substantial number of them were carried out of the modeled area to the south.

The larval duration of copper rockfish is on the order of 4-6 weeks, so based on these model results, to the extent that the larvae behave as passive particles, they will be well distributed throughout the area by the time of settlement. Given the dynamic nature of currents in this area, considerations of larval drift and dispersal are probably not as important in siting reserves as are other factors, such as quality of juvenile and adult habitat.

Increase in Abundance of Copper Rockfish Larvae Due to Reserves

Based on a recent survey estimate, there are 2.141×10^6 copper rockfish in the San Juans (W. Palsson, Washington Department of Fish and Wildlife, pers. comm.). Assuming a mean length of 30 cm, a 1:1 sex ratio, and a mean of the fecundity relationships in Washington et al. (1978), and DeLacy et al. (1964), this population would produce 5.274×10^{10} larvae per year. Assuming that the reserves in the San Juans are 10% of the total area, and that they are as effective in increasing larval production as the EUP is, the reserves would produce 2.900×10^{11} larvae, or 5.5 times the number produced by the current population.

Can the Increase in Larval Abundance of Copper Rockfish Be Detected by Ichthyoplankton Sampling?

We used results of the modeled increase in larval production and the modeled drift of larvae to examine the question of whether ichthyoplankton sampling could be used to monitor the enhanced larval production from the MPAs. Larvae produced by the present population were distributed evenly throughout the area. Those produced in the 16 present and proposed MPAs after they were established and became fully operational were distributed according to the results of the modeled drift produced by the GNOME/TAP model. These larval abundances were binned into a 2 by 2 km grid that was established throughout the San Juan Island area (Fig. 8). The error structure of the larval rockfish catches of Weiss (L. Weiss, U. Washington School of Fisheries and Aquatic Science, pers. comm.) was applied to these data. A sample using the same procedures as Weiss was then collected at each of the 359 grid stations during each of simulated 1,000 survey cruises before and 1,000 cruises after all the MPAs became fully operational.

Figure 9 shows a comparison of these simulated ichthyoplankton surveys. There is no overlap in the results of this simulated sampling before and after the reserves are established. The mean catch of larvae before the reserves are established is less than 500 larvae per 10 m^2, while the mean catch after the reserves are established is about 1,400 larvae per 10 m^2. Clearly the increased production of larvae by copper rockfish in the reserves can be detected by ichthyoplankton sampling. We did not investigate the time course of the increase in larval production, and how soon after the reserves are established that the increase can be detected.

Will MPAs in the San Juan Islands Result in Enhanced Recruitment of Copper Rockfish?

One of the other target species prompting the establishment of MPAs in the San Juans is the lingcod (*Ophiodon elongatus*). It is a voracious piscivore on the reefs, and grows faster and larger than the copper rockfish. A result of protection in the MPAs might be that lingcod will consume young fish that try to recruit to the reserves, and in time the reserve will be home to large lingcod and few other fish. To increase recruitment of copper rockfish and other fish that co-occur as adults with lingcod, it might to necessary to ensure that their juvenile as well as adult habitat is identified and protected.

Conclusions

The concept of MPAs is very attractive as a fisheries management tool and for other ecological and social reasons. MPAs have been shown to increase the number and size of fishes within them, and increase the diversity of the community associated with them. The spillover of adults from reserves to nearby fished areas has been documented in several places. Theoretical benefits of reserves relative to recruitment “seeding” have been elucidated, however few field studies have been conducted to measure these effects. Increased egg and larval production resulting from establishing reserves should be detectable by plankton sampling once the reserves are functioning. The recruitment benefits of the reserves, both within the reserves and in adjacent areas might be more difficult to demonstrate, since many factors besides egg and larval production are involved in the recruitment process. For MPAs to be effective in enhancing recruitment, the population must be recruitment-limited in the first place, and protection of juvenile as well and adult habitat might be required. Recruitment considerations and studies should accompany plans for establishing and monitoring MPAs.

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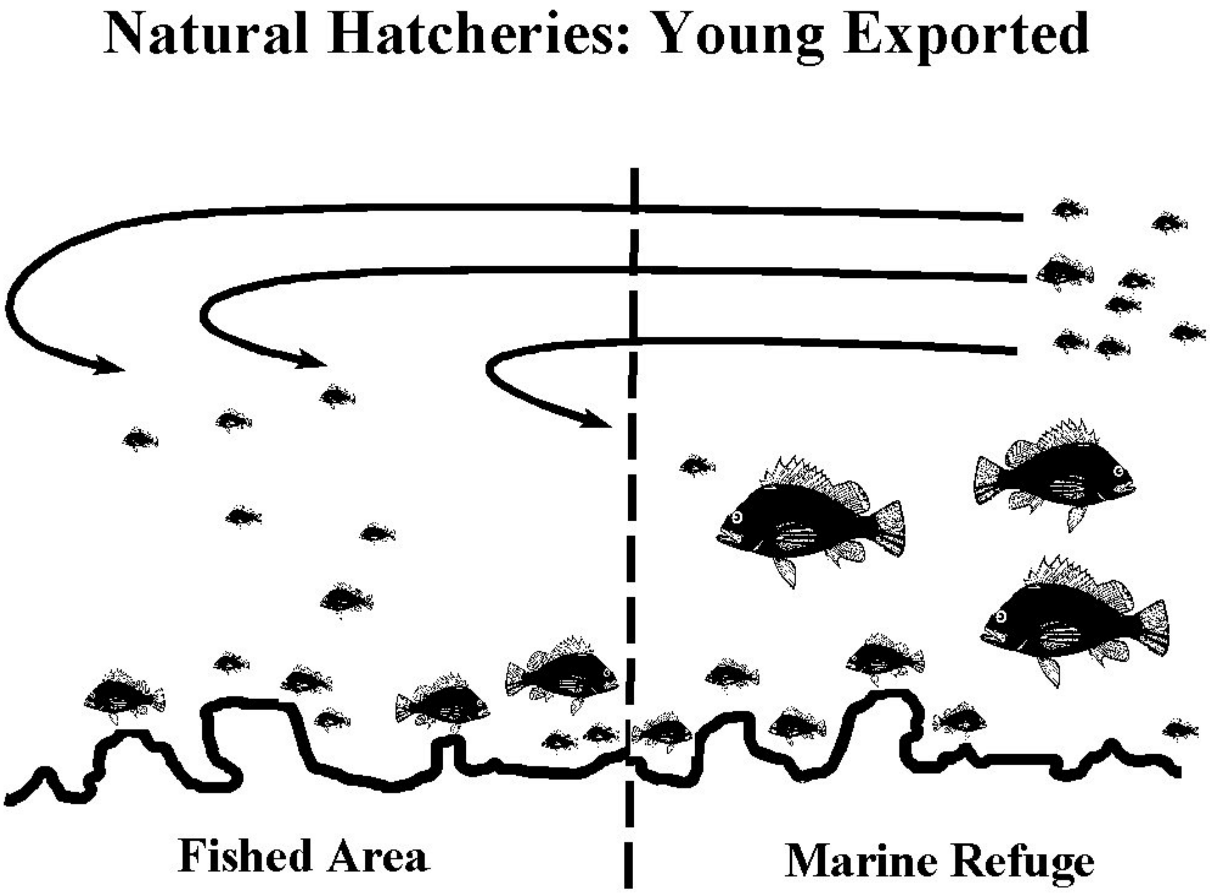

Figure 1. -- Conceptual model of the relationship of MPAs to recruitment of targeted populations. From Wayne Palsson, Washington Department of Fish and Wildlife. (pers.comm).

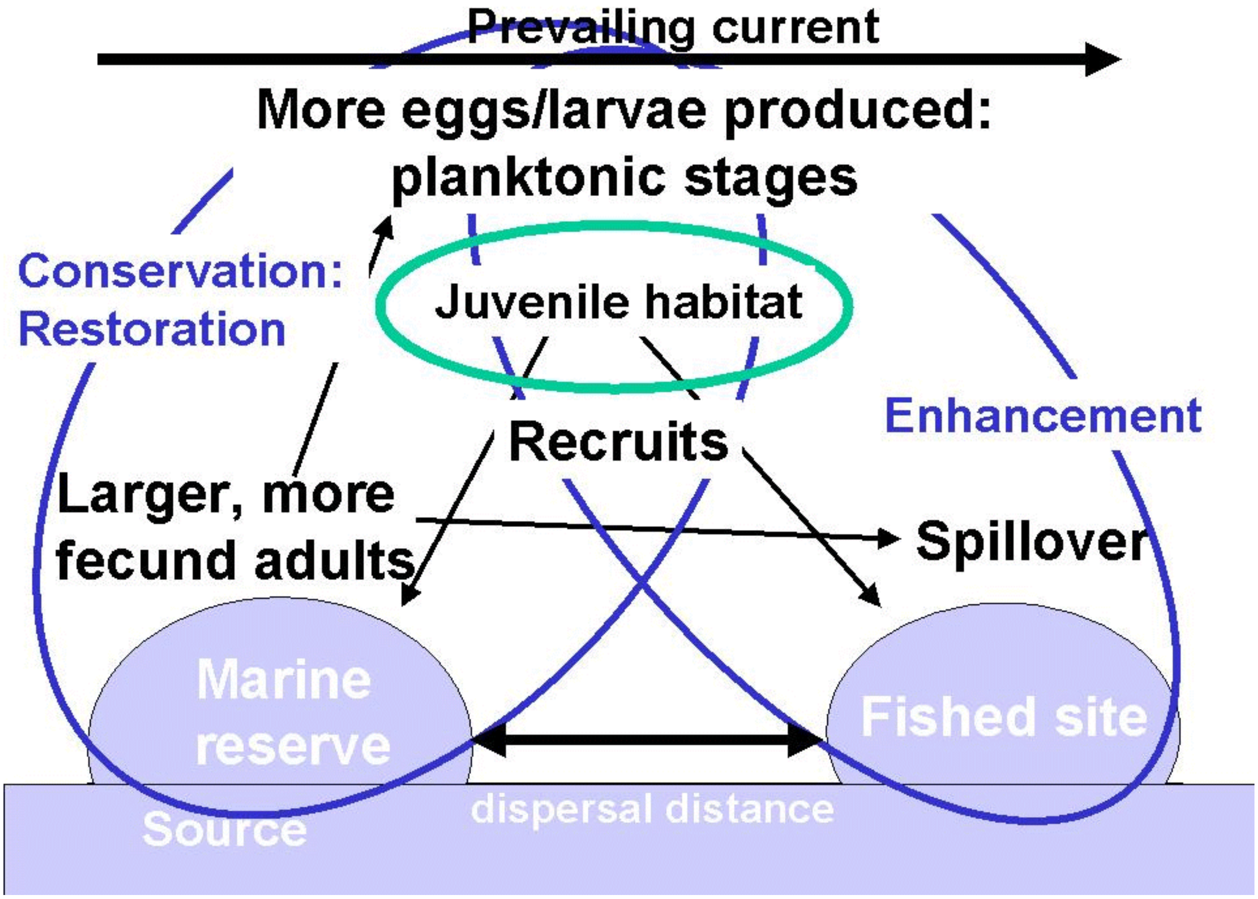

Figure 2. -- Conceptual model of the effects of MPAs.

Figure 3. -- The location of the San Juan Islands, Washington.

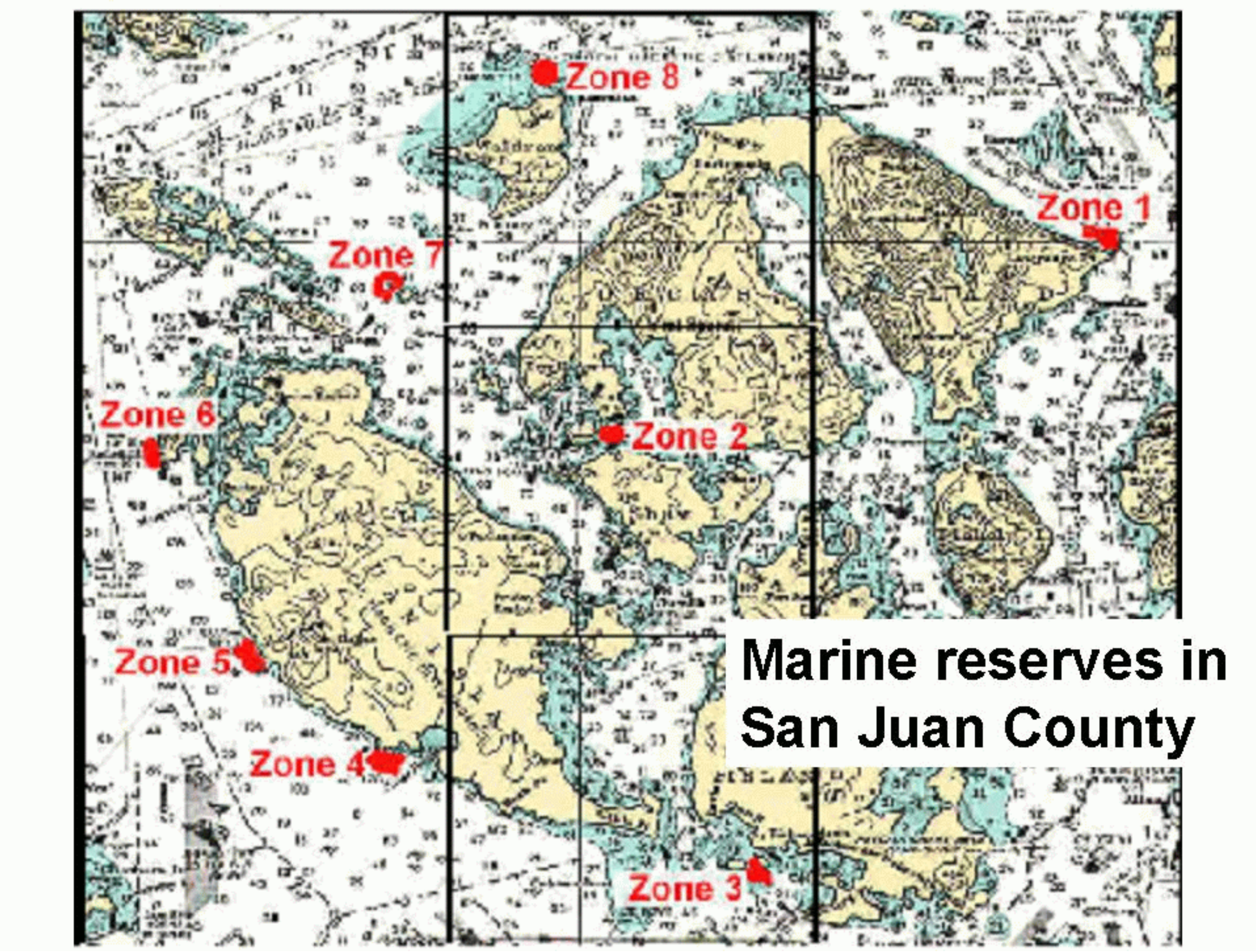

Figure 4. -- Locations of MPAs established by San Juan County Marine Resources Committee.

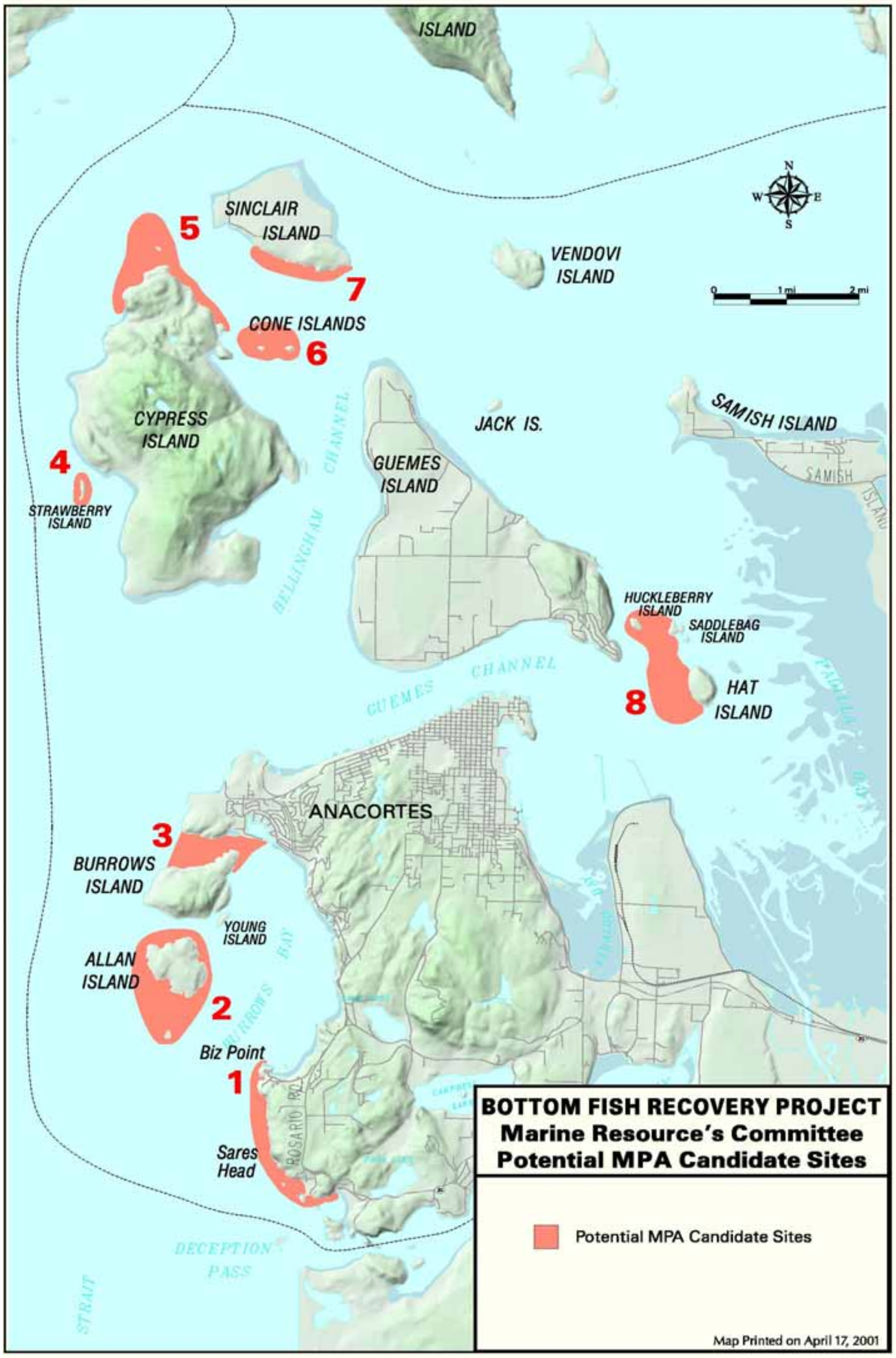

Figure 5. -- Locations of MPAs proposed by Skagit County Marine Resources Committee.

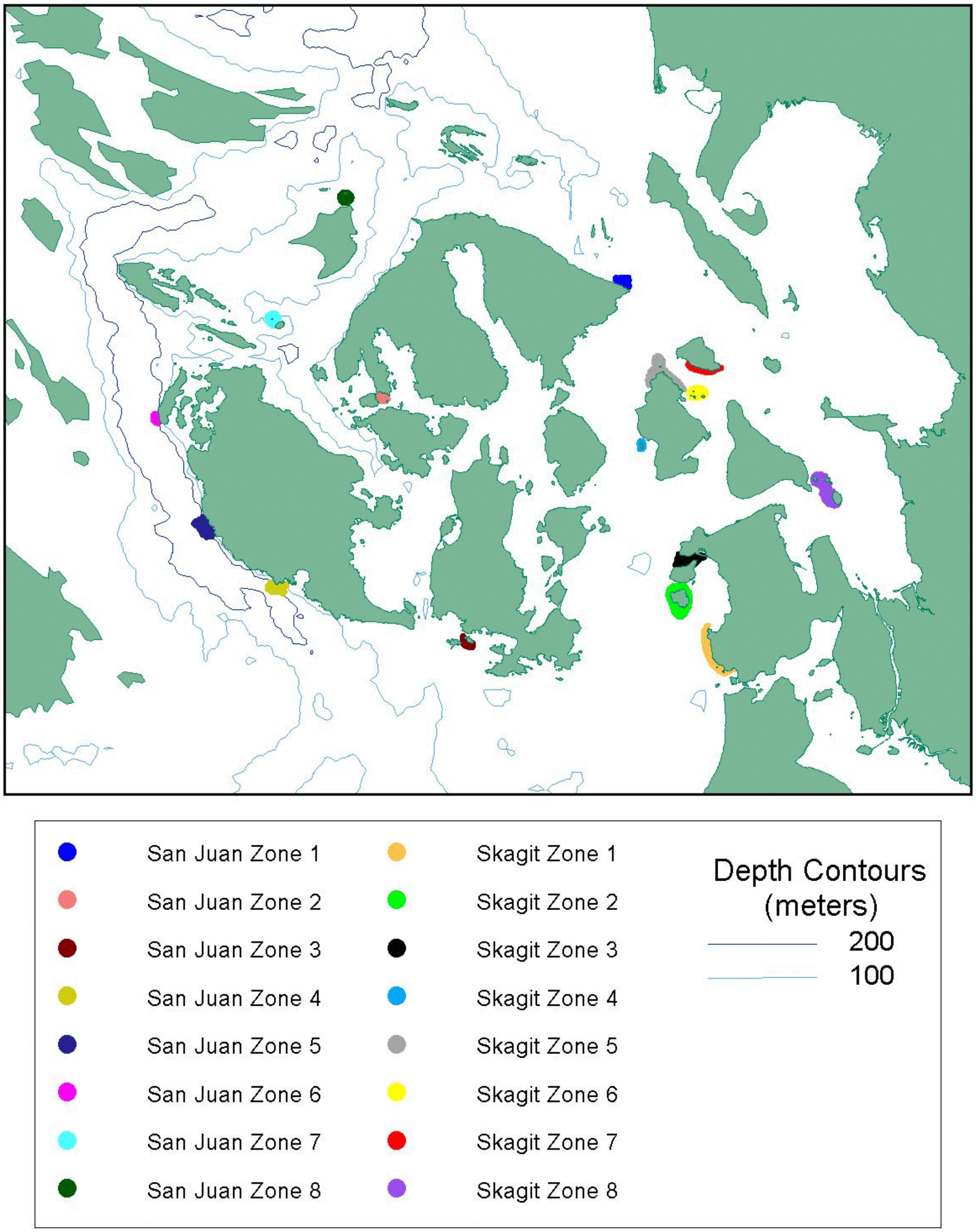

Figure 6. -- Initial locations of particles at San Juan Island MPAs used to model larval copper rockfish dispersal.

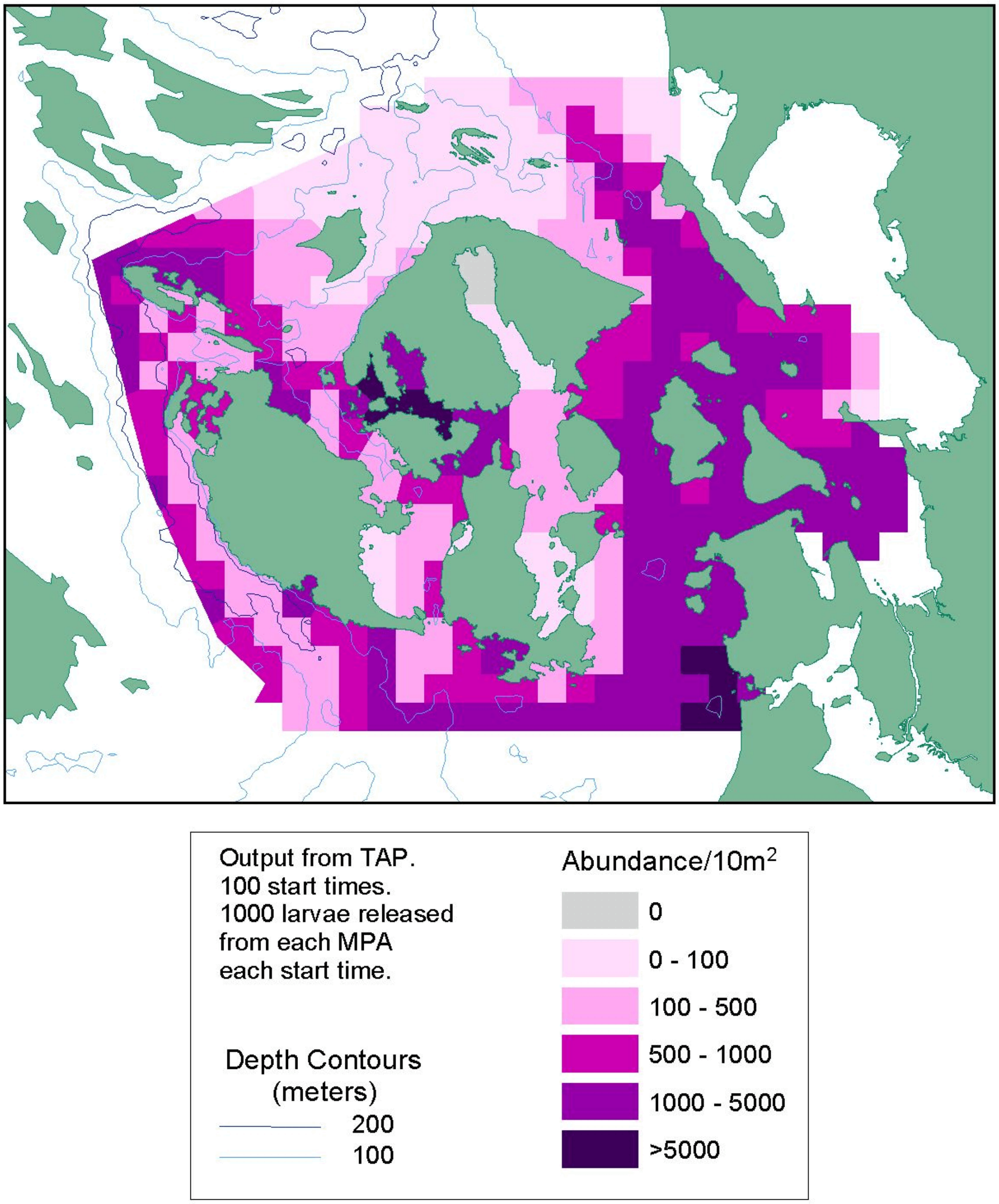

Figure 7. -- Simulated spatial distribution of copper rockfish larvae 72 hours after their birth in the 16 proposed MPAs. The Trajectory Analysis Planner (TAP) program released 1,000 particles at each of 100 times over a 24 hour period in each MPA, and then modeled their movement for 72 hours. The color of each cell indicates the number of larvae in the cell, after rescaling the number of modeled particles to be the number of larvae per 10 m^2 of surface area.

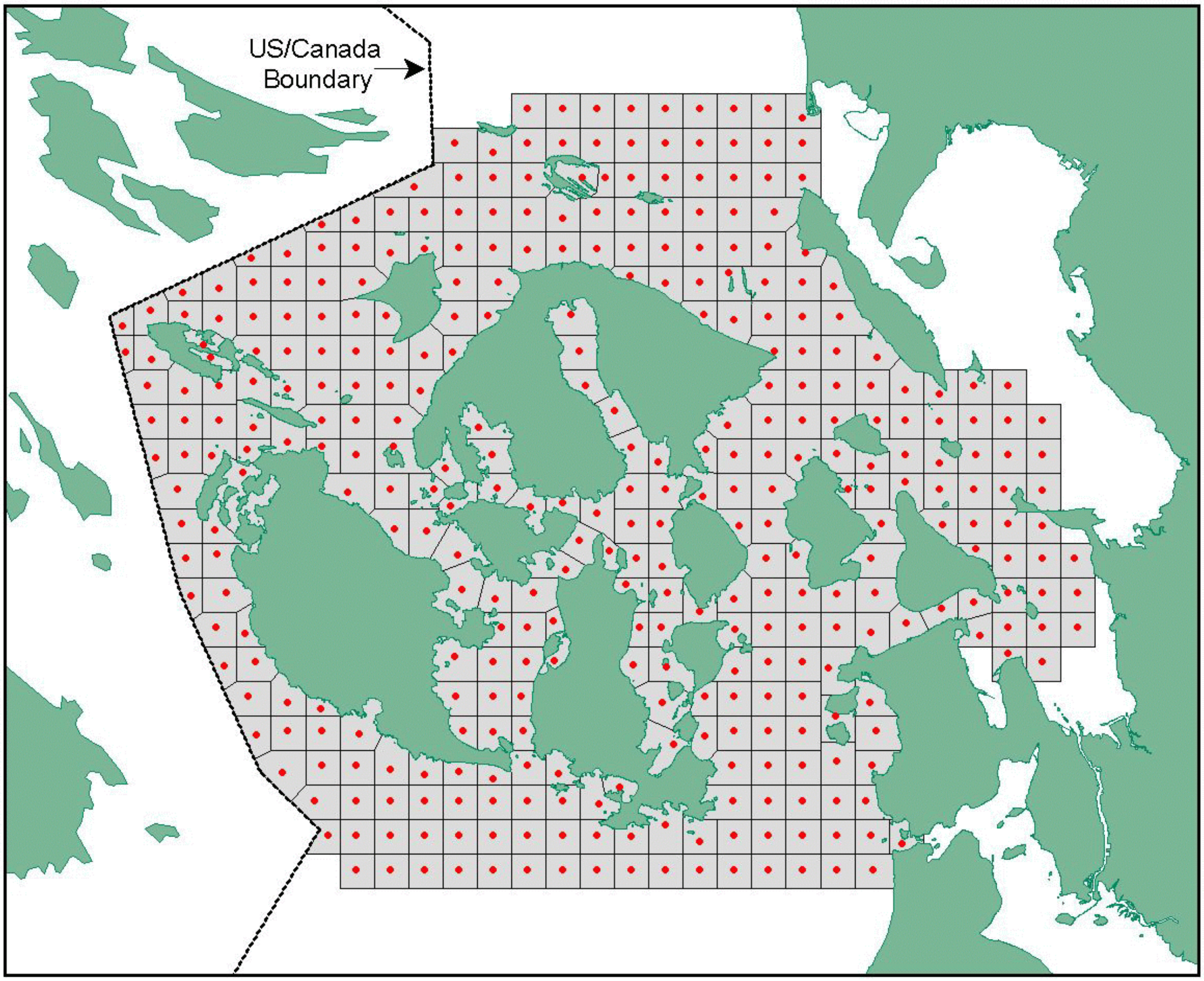

Figure 8. -- Simulated sampling grid with a station in each grid cell for evaluating effects of MPAs on copper rockfish larval production in the San Juan Islands.

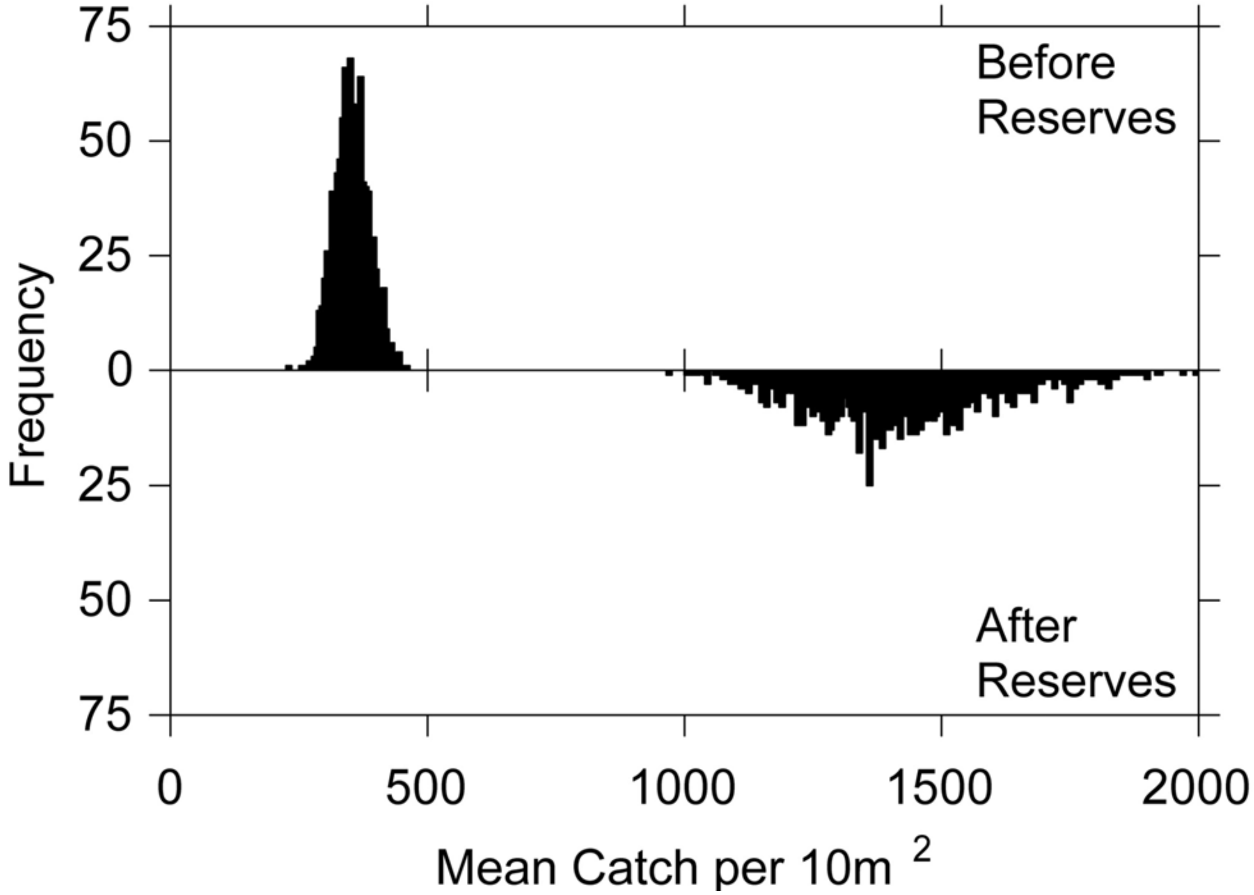

Figure 9. -- Frequency distribution of sample mean abundances (number of larvae per 10 m^2 of surface area) of larval copper rockfish from simulated surveys in the San Juan Island area. Top panel is sample means from 1,000 simulated surveys with no additional larval production from the MPAs. Bottom panel is sample means from 1,000 simulated surveys of larval copper rockfish that include the predicted number of larvae produced in the MPAs.

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