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Authors: Verkamp, Hannah J., Nooij, Joshua, Helt, William, Ruddock, Kevin, Williams, Anna Gerber, et al.

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SCOPING BAY SCALLOP RESTORATION IN RHODE ISLAND: A SYNTHESIS OF KNOWLEDGE AND RECOMMENDATIONS FOR FUTURE EFFORTS

HANNAH J. VERKAMP,[1]* JOSHUA NOOIJ,[1,2] WILLIAM HELT,[3] KEVIN RUDDOCK,[3] ANNA GERBER WILLIAMS,[4] M. CONOR MCMANUS[4] AND N. DAVID BETHONEY[1]

[1]*Commercial Fisheries Research Foundation, Saunderstown, RI, USA;* [2]*Northeastern University, Boston, MA, USA;* [3]*Rhode Island Chapter, The Nature Conservancy, Providence, RI, USA;* [4]*Division of Marine Fisheries, Rhode Island Department of Environmental Management, Jamestown, RI, USA*

ABSTRACT The bay scallop is a culturally important species that once supported significant fisheries along the U.S. east coast. Mass population declines in the 1900s led to a nearly total loss of the fishery in most states, including Rhode Island. In certain areas, intensive, long-term restoration efforts have effectively restored scallop populations and fisheries on a small scale, but indicate that such plans must be scoped specific to systems. In an effort to support the development of an upcoming Rhode Island Shellfish Restoration Plan, relevant knowledge on bay scallops was collated and summarized, and this information was used to create a habitat suitability index that can act as a guide to identify suitable restoration sites for renewed bay scallop restoration efforts in one of the largest coastal salt ponds in Rhode Island, Point Judith Pond. Point Judith Pond was once the epicenter of the bay scallop fishery in the state of Rhode Island, and the ranked index suggests multiple sites throughout the pond are likely to once again provide adequate habitat for bay scallops. Restoration strategies such as caged spawner sanctuaries and the release of competent larvae in areas identified as suitable by the index are recommended for future restoration planning of this species.

KEY WORDS: shellfish, restoration strategies, habitat suitability index, enhancement, restoration planning

INTRODUCTION

In the late 19th century and much of the 20th century, robust populations of bay scallops supported a lucrative fishery in the United States (U.S.) (MacKenzie 2008). Bay scallop populations drastically declined in the late 1900s due to several factors, including widespread algal blooms in important bay scallop habitats (Blake & Shumway 2006). The resulting mass mortalities led to population collapses and a near total loss of the fishery coastwide (MacKenzie 2008). The high potential commercial value of bay scallops, along with their historic cultural significance, has prompted the implementation of various restoration efforts along the coast (Fegley et al. 2009). Nearly four decades after the population crashes, however, most bay scallop populations remain highly variable and have not recovered to historic levels.

Rhode Island had a prolific bay scallop fishery in the first half of the 1900s, and a culturally significant fishery until 1985 when a brown tide algal bloom wiped out most of the wild populations (MacKenzie 2008). There have been multiple efforts by groups including the Rhode Island Department of Environmental Management (RIDEM), the North Cape Shellfish Restoration Program (NCSRP), and Save the Bay (STB), to restore Rhode Island bay scallop populations since the 1970s. Such efforts have only been conducted for short periods of time, leading to only short-term increases in populations. As a result, RI bay scallop harvest remains negligible [National Oceanic and Atmospheric Administration (NOAA) 2021]. In an effort to catalyze renewed restoration efforts in the state, relevant knowledge on bay scallop biology and restoration from both regional and local scales was compiled and summarized. This information was then used to create a habitat suitability index for bay scallops in one of the largest coastal salt ponds in Rhode Island, Point Judith Pond. The goal of this work was to provide insight for the Rhode Island Shellfish Restoration Plan being developed by RIDEM.

*Corresponding author. E-mail: hverkamp@cfrfoundation.org
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SPECIES BACKGROUND

Biology, Life History, and Ecology

The bay scallop (*Argopecten irradians* Lamarck) is a bivalve that inhabits shallow coastal waters along the east coast of the U.S. and Gulf of Mexico. Three subspecies of bay scallop are found in the U.S.: the Gulf bay scallop (*Argopecten irradians amplicostatus*), southern bay scallop (*A. i. concentricus*), and northern bay scallop (*A. i. irradians*). The northern bay scallop ranges from Cape Cod, MA to New Jersey and is the focus of this work. As a result, the following information related to bay scallop biology and ecology is most relevant to *A. i. irradians.*

Bay scallops are environmentally sensitive; their breeding and growth patterns are highly dependent on factors such as salinity and temperature, with optimal conditions varying across life stages. Overall, bay scallops can survive a relatively large range of salinity, with extreme salinities of 10–38 reported, however a salinity greater than approximately 24 is best for growth and survival for the northern subspecies (Tettelbach & Rhodes 1981, Oesterling 1998, Broadaway & Hannigan 2012, Brand 2016). Survivable temperatures range from below 0°C to over 32°C, yet optimal temperatures for the northern subspecies fall within the range of approximately 20°C to 27°C (Leavitt et al. 2010a, Williams et al. 2015, Brand 2016).

Bay scallops are functional hermaphrodites, and breeding starts when the bay scallop is approximately 1 y of age (MacKenzie 2008, Robinson et al. 2016). In the northeast U.S., spawning begins in late spring, usually in late May or June, when water temperatures reach approximately 22°C, and continues until late summer (Belding 1910, Bricelj et al. 1987). Bay scallops can spawn through a season, and in some areas may spawn more than once a year. For example, a second spawning event in the later summer or early fall months has been observed in several northern bay scallop populations (Taylor & Capuzzo 1983, Tettelbach 1991, Hall et al. 2015). Such additional spawning events have the potential to increase the population by up to 58.3% in one spawning cycle compared with a single-spawning population (Hall et al. 2015).

Bay scallops have a rapid growth rate and relatively short life cycle (Robinson et al. 2016). After fertilization, bay scallops begin a pelagic larval phase, which lasts approximately 14 days; upon completion of this phase juveniles settle on epibenthic substrate (MacKenzie 2008, Robinson et al. 2016). Bay scallops' preferred settlement is eelgrass (*Zostera marina*), but juveniles have been shown to settle on other available substrates, such as macroalgae or oyster shells (Carroll et al. 2010, Hernandez Cordero & Seitz 2014). Juveniles require settlement in areas where the substrate can act as a refuge from predation, as bay scallops smaller than 30 mm are highly susceptible to epibenthic and benthic predators such as shrimp, crabs, and sea stars (Pohle et al. 1991, Irlandi et al. 1995, Hernandez Cordero & Seitz 2014, Lefcheck et al. 2014). Once juveniles reach approximately 30 mm they drop to the benthic substrate and continue to grow rapidly until overwintering (MacKenzie 2008, Robinson et al. 2016). Upon survival through their first winter, bay scallop shells typically develop a distinct growth line, which can be used to help visually identify an adult scallop, particularly in the northern range of the species (Marshall 1960, Mackenzie 2008). Bay scallops live for approximately 2 y, with a lifespan ranging from 20 to 26 mo (Marshall 1960, Mackenzie 2008). As a result, a population at any given time consists solely of 2 y-classes, which results in naturally highly variable populations (Robinson et al. 2016).

Bay Scallop Fishery

The iconic commercial bay scallop fishery was historically a significant industry in local economies across the U.S. east coast, with the first documented landings dating as far back as the 1800s (MacKenzie 2008). Dredging was the most common harvest method during the height of the fishery, and the New England region typically accounted for the majority of coastwide landings (MacKenzie 2008). Coastwide commercial landings peaked in 1962 when the total harvest exceeded 3 million pounds (all pounds reported as meat weight, shells excluded); the ex-vessel value of the commercial fishery subsequently peaked in 1982, when the total harvest produced over $11 million, which equates to over $32 million in 2022 (NOAA 2021). Bay scallop populations have declined drastically since the mid-20th century, however. Factors such as widespread harmful algal blooms (HABs), which can cause decreased feeding efficiency and mortality of bay scallops, and an extensive eelgrass wasting disease, which caused a loss of suitable habitat, led to devastating population collapses in most locations, and nearly a total loss of the fishery coastwide (Gallager et al. 1989, Goldberg et al. 2000, Tettelbach et al. 2002, Fonseca & Uhrin 2009). By 1986, less than 1 million pounds of bay scallops were landed coastwide, and rapid declines continued throughout the 2000s when total U.S. harvests fell below 10,000 pounds (NOAA 2021). Coastwide landings have since increased, with total annual landings averaging approximately 200,000 pounds over the past decade, but have not recovered to historic levels (NOAA 2021). The recreational harvest of bay scallops has also long represented a culturally important fishery in many places, but landings data for this fishery are not available (MacKenzie 2008). Current bay scallop fisheries remain sparse and mostly operate on a local, artisanal level.

The restoration of collapsed bay scallop populations, as well as the enhancement of natural populations, to levels that can support fisheries represents an opportunity for states to increase fisheries revenue, diversify fisheries landings, and expand the opportunity for recreational fishing. Given the life history of bay scallops, fishery harvest can be managed in a manner that is sustainable with minimal impacts on the year-to-year population levels. As a result of their 2-y life cycle, after they spawn during their second year, adult bay scallops will be removed from the population regardless of whether it is due to natural mortality or fishery harvest. Restricting harvest to adult scallops, as determined via the presence of growth lines, and closing the fishery during months of spawning activity, can thus allow for sustainable fishery removal of bay scallops.

In some places, intensive, long-term restoration and enhancement efforts have been successful in restoring or maintaining bay scallop populations and fisheries on a small scale; the degree of success of these efforts varies widely however. For example, after a population collapse in the 1980s, Long Island Sound northern bay scallop populations remained extremely low, hovering around 2% of historic levels (Tettelbach et al. 2013). Extensive restoration strategies were implemented in 2006; by 2010, larval recruitment had increased by 11–32 times that of prerestoration levels in different locations (Tettelbach et al. 2013). The fishery was also rebuilt as a result of these efforts, and from 2010 to 2013, Long Island bay scallop fishery landings represented an increase in 13 times compared with the years prior to restoration (Tettelbach et al. 2015). This increase in fishery landings produced an increase of at least $2 million to the local economy, with a gross economic benefit of at least $20 million (Tettelbach et al. 2015).

Long-term population enhancement efforts have allowed the northern bay scallop fishery to remain a significant source of revenue for Massachusetts, especially the islands of Nantucket and Martha's Vineyard (Herr et al. 2012). This represents one of the only remaining wild/natural bay scallop fisheries in theU.S.. In 2019, commercial harvest of bay scallops produced an ex-vessel value of $1.5 million in the state of Massachusetts (NOAA 2021). Bay scallops represent the largest commercial fishery for Nantucket, and although more recent data is not publicly available, the ex-vessel value of bay scallops in Nantucket in 2010 was nearly $650,000 (Herr et al. 2012). In addition, restoration of the southern bay scallop has also been an ongoing effort in Florida since the 1990s (Arnold 2009). Although much smaller than that in New England states, southern bay scallops supported a commercial fishery in Florida until populations crashed in the late 1900s, and bay scallops have not been harvested commercially since 1993 (NOAA 2021). Long-term restoration efforts have allowed recreational harvest to continue in Florida, however, and it is likely that continued efforts and effective management measures will continue to support functional bay scallop populations in that state (Arnold 2009).

Sources of Stress

Bay scallops face a suite of stressors that interact to influence population success and growth. The primary threats to bay scallop populations include a loss of suitable habitat, predation, impaired water quality, HABs, parasites and diseases, recruitment limitation due to population collapse, and anthropogenic climate change. Together, these natural and anthropogenic stressors have contributed to keeping bay scallop populations at levels too low to support significant fisheries across the U.S. coast, and these factors should be considered in restoration planning.

A loss of suitable bay scallop habitat, particularly eelgrass, has been observed all along the U.S. east coast (Fonseca & Uhrin 2009). Bay scallops are highly dependent on epibenthic surfaces to settle on at the conclusion of the larval stage, as these surfaces protect vulnerable size-classes from excessive predation (Belding et al. 1910, Pohle et al. 1991, Hernandez Cordero & Seitz 2014). Unfortunately, eelgrass beds have been declining since the 1930s, when a widespread wasting disease wiped out many populations (Fonseca & Uhrin 2009, Oreska et al. 2017). Eelgrass beds have not fully recovered, due to factors such as decreased water quality, increased turbidity, and low annual recruitment (Fonseca & Uhrin 2009, Kennish 2009). Techniques used by commercial shellfisheries can affect habitat as well. For example, some large-scale fisheries primarily use dredge fishing to maximize efficiency, however this technique can harm eelgrass fields (Bishop et al. 2005). Although bay scallops have been shown to settle on alternative epibenthic surfaces when eelgrass is unavailable, such as macroalgae, oyster (or other shellfish) shell, and a variety of other hard benthic substrates (Marshall 1960, Carroll et al. 2010), survival of scallops in these alternative habitats may be lower than that in eelgrass (Hernandez Cordero et al. 2012). Bay scallop abundance has been shown to positively correlate with seagrass density, so restoration programs should prioritize areas with ample seagrass habitat to maximize the chances of successful restoration (Carroll et al. 2022).

Predation is another significant threat to bay scallop populations. The main predators of bay scallops in the northeast Atlantic include sea stars, crabs, and oyster drills (Morgan et al. 1980, Ordzie & Garofalo 1980, Dinsdale 1991, Carroll et al. 2022). In addition, very small juveniles (<1 mm) are susceptible to epibenthic predators such as amphipods, isopods, and shrimp (Lefcheck et al. 2014). Predators have always been a large source of bay scallop mortality; in addition, the invasive green crab has rapidly increased in numbers in the northern Atlantic in recent years due to the wide range of environmental conditions tolerated by this species and a lack of natural predators in this region (Matheson et al. 2016). These increases in crab populations have led to a higher predation pressure for juvenile bay scallops (Matheson et al. 2016). Habitat also plays an interactive role in shaping predation pressure. For example, predation pressure is higher within very patchy fields of eelgrass when compared with larger fields due to the relatively large periphery (Irlandi et al. 1995, Carroll & Peterson 2013). In addition, extensive green crab populations can have negative effects on eelgrass beds, as they uproot marine plants in search of benthic prey (Neckles 2015, Matheson et al. 2016). This uprooting of eelgrass by green crabs removes important protective eelgrass habitat and creates patchy fields; as such, the removal of eelgrass by predators increases predation pressure by more than direct consumptive effects (Neckles 2015).

Harmful brown, red, and rust tide algal blooms are thought to be largely responsible for many of the mass bay scallop population collapses in the 1980s (MacKenzie 2008), and HABs continue to pose threats to already struggling bay scallop populations. Harmful algal blooms, which are caused by dense colonies of over 200 species of microalgae such as dinoflagellates, diatoms, cyanobacteria, and others, have long occurred in marine ecosystems; however, the incidence of HABs has increased over the past several decades, likely related to decreasing water quality and climate change (Landsberg 2002, Hallegraeff 2003). Harmful algal blooms can kill bay scallops directly and/or lead to starvation, resulting in decreased growth and spawning potential of scallops (Bricelj & Kuenstner 1989, Gallager et al. 1989). Near-complete recruitment failure of bay scallops has been observed following HABs, and HABs can also result in decreased eelgrass beds and a further loss of suitable habitat for bay scallops (Bricelj et al. 1987, Cosper et al. 1987).

Impaired water quality also poses a threat to bay scallop populations. For example, nutrient loading as a result of runoff from agricultural and developed areas has led to an increase in eutrophic, anoxic bodies of water, and such conditions can negatively impact bay scallop growth and increase mortality (Peterson et al. 1996, Wall et al. 2013). Food quality is also related to water quality, with eutrophic areas potentially having increased concentrations of nutrient-poor or toxic food sources for bay scallops compared with locations with higher water quality (Wall et al. 2013). Increased turbidity and volatile suspended solids have also been correlated with increased mortality in southern bay scallops (Leverone 1995). In addition, increasingly impaired water quality and eutrophication have contributed to keeping eelgrass populations low, thus further contributing to decreases in bay scallop populations (Short et al. 1995, Fonseca & Uhrin 2009, Kennish 2009).

Parasites and diseases pose additional threats to bay scallops (Getchell et al. 2016). Parasites, such as the pea crab, have long been known to infect bay scallops and can cause reduced growth and impaired reproduction (Kruczynski 1972, Bologna & Heck 2000). In addition, whereas disease has always been a threat to natural populations, the relatively high density of bay scallops in planted populations results in restored bay scallop populations being more susceptible to pathogens, and bay scallops grown in bottom gear are more susceptible to parasites compared with those kept in surface gear (Karlsson 1976, Tobi & Ward 2019). Pollution and upstream runoff can introduce new pathogens to bodies of water (Getchell et al. 2016), and the release of hatchery-reared scallops into a wild population poses the risk of introducing new pathogens into a system. Whereas antibiotic treatment could provide a short-term solution, this increases the risk of antibiotic resistant pathogens (Karlsson 1976). Quarantine of imported scallops could limit the risk of disease-related mortality in planted populations. After settling, frequent monitoring is an important factor in mitigating disease in restored populations.

A combination of the aforementioned factors has contributed to the current low population levels for bay scallops across the U.S. east coast. Small bay scallop populations now face an additional threat, recruitment limitation, which further contributes to keeping population levels low (Tettelbach et al. 2013). Recruitment limitation refers to the concept that the density of a local population may be limited by the rate at which larvae are able to settle and survive (i.e., recruitment to the population) in a given area (Chesson 1998). Due to the short lifespan of bay scallops, the continued survival of a population is highly dependent on the recruitment success from the prior year (Conrad & Heisey

2000). In addition, because bay scallop populations are often considered discrete units with limited larval exchange among systems, recruitment is dependent on the abundance of spawning adults within a given population (Peterson & Summerson 1992, Peterson et al. 1996, Orensanz et al. 2016). Low abundance of adults can lead to low larval supply; this can result in higher relative mortality and lower relative recruitment compared with when adult abundance is higher (Peterson & Summerson 1992, Arnold et al. 1998). Low recruitment can then result in a small year-class that, upon maturation, is once again unable to produce enough larvae to increase the population (Peterson & Summerson 1992, Orensanz et al. 2006). Increased recruitment has been shown to positively correlate with adult abundance (Oreska et al. 2017), and restoration efforts that aim to overcome such limitations have shown success in increasing adult bay scallop abundance (Tettelbach et al. 2013, 2015).

Finally, anthropogenic climate change and ocean acidification are growing concerns for bay scallop populations. Both temperature and salinity have been shown to significantly affect the growth, survival, and spawning of bay scallops (Tettelbach & Rhodes 1981, Barber & Blake 2006, Leavitt et al. 2010a). In addition, increasing temperatures are likely to increase predation risk through the increase or introduction of new predators as more southern species such as the cownose ray (*Rhinoptera bonasus*), a known predator of bay scallops, exhibit northward range expansions (Peterson et al. 2001, Mackenzie 2008). Increasing water temperatures can also exacerbate the impact of some diseases and parasites, thus further stressing bay scallop populations (Getchell et al. 2016). Further, increased acidification has been shown to limit shell growth in larval bay scallops and can lead to decreased survival (Talmage & Gobler 2010, Broadaway 2012, White et al. 2013, 2014, Gobler et al. 2014). Hypoxia, which is more likely to occur in climate-induced eutrophication events, also significantly affects development and reduces growth rate in juvenile bay scallops (Chun-de & Fu-sui 1995, Moss et al. 2011, Gobler et al. 2014). Adaptive management strategies are needed to deal with the challenges of a rapidly changing environment, especially given the environmental constraints for bay scallop growth and breeding (Stern et al. 2011).

BAY SCALLOP RESTORATION STRATEGIES

A suite of restoration and enhancement strategies have been developed and used for bay scallops throughout the Gulf of Mexico and U.S. east coast. The primary strategies used seek to help populations overcome low natural population density and recruitment limitation, and they vary widely in terms of time and spatial scale, labor investment, and cost. Often, there is a trade-off between cost and labor requirements, and impact. In addition, in most cases, each strategy has been attempted in multiple locations with varying rates of success. As a result, for bay scallop restoration to have the greatest chance of success, a restoration plan must be developed specific to the system of interest, with strategies chosen for a given location based on biological and habitat considerations. In addition, a combination of strategies will likely yield the most successful results, with each strategy representing one tool within a larger toolkit of restoration techniques. Even after intense initial restoration efforts, ongoing enhancement of bay scallops is needed to sustain populations in the long term. The primary restoration and enhancement strategies that can be used for bay scallops are described in the following subsections.

Transplanting of Wild Scallops

The most basic strategy to enhance bay scallop populations in areas with low population density is to collect and redistribute wild scallops or naturally occurring scallop seed from areas with higher population densities. This strategy was successful in restoring bay scallop populations to levels that could support commercial harvest in Rhode Island in the 1970s, when RIDEM transplanted wild northern bay scallops from Massachusetts to Point Judith Pond, RI (Sisson 1970). The municipality of Nantucket has also been transplanting wild scallops in some capacity since 1981 through “seed relays.” There, bay scallop seed is redistributed from dense settlement areas or sites with poor grow-out conditions to other suitable habitats with ideal circulation, temperatures, depths, and dissolved oxygen levels in an effort to maximize development and future spawning success (Herr et al. 2012). Transplantation of southern bay scallops in North Carolina has also been correlated with increased recruitment (Peterson et al. 1996).

Transplantation is one of the lowest-cost and least labor-intensive methods for bay scallop restoration, but it requires a nearby area where spawning adults occur naturally (Peterson et al. 1996, Arnold 2008). This method also poses the threat of straining natural populations and making them more susceptible to catastrophic declines resulting from adverse natural events (Arnold 2008). As a result, it is not feasible as a restoration strategy in locations where bay scallop populations have been completely decimated across a large spatial area, and it should be used only as a secondary method in locations where possible to help maximize the success of other strategies.

Larval Seed Release

Another relatively low-cost strategy is to release a large number of hatchery-reared bay scallop larvae or newly settled seed in a designated area (Arnold 2008). This strategy represents a method that can help overcome recruitment limitation following a population crash (Peterson et al. 1996, Leverone et al. 2004, 2010), as well as to help overcome high mortality rates and intense predation pressure for vulnerable life stages. It is based on the idea that, by overloading an area with young scallops, even a low survival rate could allow a sufficient number of individuals to survive through maturation to form a spawning broodstock (Leverone et al. 2010, Herr et al. 2012). When using this method, bay scallop broodstock, ideally collected from nearby local waters, must be spawned in a hatchery. Larvae are then reared through most of their pelagic stage until just prior to or after metamorphosis when they are considered “competent,” that is, ready to set (Leverone et al. 2010). At this point, high densities are either free-released or released into enclosures in a particular habitat chosen to maximize successful settlement and grow out (Leverone et al. 2010).

Larval release has been used as a restoration strategy for southern bay scallops in Florida for several decades. Despite initial success, in which several populations displayed short-term increases in adult bay scallop abundance following larval release, this approach alone was not enough to restore a naturally sustaining bay scallop population in the long term

(Leverone et al. 2004, 2010). Nantucket has also been using larval release as part of their bay scallop enhancement program for many years. There, local bay scallops are spawned at a nearby hatchery, and an average of 120 million larvae, with spikes of up to 300 million, are deployed annually, usually across two or more release events (Herr et al. 2012). Hatchery spawning is timed so that larvae can be released immediately following metamorphosis on an incoming tide, which helps increase retention and maximize settlement (Herr et al. 2012).

This method is relatively simple to execute, and it is not as costly as methods that require the growth of bay scallops in hatcheries through the juvenile or adult stages, which are discussed below. Larval/seed release does require significant research and labor to be successful, however (Herr et al. 2012). For example, reared scallops must be properly acclimatized for conditions in the natural environment prior to release, and the timing of release must be when conditions are optimal for early life stages to maximize survival (Leverone et al. 2004, Liu et al. 2015). In addition, whereas the release of several million larvae will generally ensure at least some scallops survive and populate an area regardless of location, the location is crucially important for the overall success of the release (Herr et al. 2012). Partially enclosed areas with circulation patterns and flushing rates that promote retention are necessary to form patches of scallops that survive to adulthood (Leverone et al. 2010). Adequate habitat for the newly settled scallops to attach to is equally important. In addition, larval/seed release strategies are very vulnerable to arbitrary events such as a large flood or storm, uncharacteristically high predation pressure, or an unexpected heatwave. As a result, this strategy is best used in combination with another strategy that focuses on adult scallops.

Grow-Out Culture and Spawner Sanctuaries

Perhaps the most widely used, and potentially the most successful, bay scallop restoration strategy is to grow-out hatchery-reared scallops in the natural environment, thus creating a "spawner sanctuary" for broodstock. This method aims to supply a population with enough individual scallops that spawn in the wild to overcome recruitment limitation (Tettelbach et al. 2011). When using this strategy, scallops are reared in hatcheries to the juvenile or adult stage and then introduced to the natural environment. There are various approaches for release, ranging from free-planting scallops in a dense area, to enclosing individuals in aquaculture gear through the spawning period (Tettelbach et al. 2002, 2011). Although free-planting (i.e., releasing scallops directly on the substrate) is the least costly and labor-intensive approach, it is also typically the least successful due to high mortality rates (Tettelbach et al. 2011). Most often, spawner sanctuaries are created by keeping scallops in enclosures, including bottom cages, floating rafts/cages, corrals, and lantern nets, which greatly increases costs and labor requirements but typically increases survival and success (Arnold et al. 2005, Fegley et al. 2009, Tettelbach et al. 2011).

Caged spawner sanctuaries provide protection from predation and ensure that scallops remain in close vicinity, thereby increasing the chances of successful spawning and fertilization (Arnold 2008, Kirk et al. 2020). Oftentimes, hatchery-reared scallops are only available as juveniles; in this case, scallops must be grown out in cages throughout the winter months before they can form a broodstock and spawn (Goldberg et al. 2000). Wire/mesh cages have been used most extensively for bay scallop restoration, especially in New England, however lantern net rearing has shown considerable success in Long Island (Hancock et al. 2005, 2006, 2007, DeAngelis et al. 2008, 2009, Herr et al. 2012, Tettelbach et al. 2015, Kirk et al. 2020).

Caged spawner sanctuaries require regular maintenance and cleaning to minimize biofouling of the cages, as biofouling can reduce water flow and food availability, thereby resulting in reduced growth and condition, and increased mortality of stocked scallops (Goldberg et al. 2000, Leavitt et al. 2010b, Tettelbach et al. 2014). Coating the nets in a protective silicone layer can limit biofouling; whereas this increases supply costs, it could reduce labor needed for maintenance (Tettelbach et al. 2014). In addition, stocking density is a primary consideration when keeping scallops in cages (Leavitt et al. 2010b). Overcrowding of scallops can result in high levels of food competition, decreased growth rates, as well as physical injuries and/or death (Rhodes & Widman 1984, Leavitt et al. 2010b, Tettelbach et al. 2015, Tobi & Ward 2019). A cover of approximately 50% of cage surface area is generally recommended to limit the effects of overcrowding (Leavitt et al. 2010b), which means many enclosures are necessary to effectively grow-out a sufficient number of scallops. Further, appropriate conditioning of hatchery-reared scallops is necessary when deploying spawner sanctuaries to ensure scallops survive upon introduction to the natural environment, as well as to maximize reproductive condition and output (Tettelbach et al. 2002).

Seed Management

An additional strategy that can help bolster restoration efforts is the use of spat bag collectors as nurseries for young bay scallops. This strategy focuses on protecting young scallops during vulnerable life history stages and attempts to increase the chances that a scallop will survive and grow to adulthood. Spat collector bags, which collect pelagic scallop larvae just prior to settlement, increase the surface area on which scallops can settle, and they can also serve as artificial "nurseries" for grow-out by providing protection from predation (Fegley et al. 2009, Tobi & Ward 2019). In North Carolina, southern bay scallops have been successfully collected and grown in spat bags deployed in their natural environments beyond the size at which scallops typically detach from settlement surfaces, and at which they are less vulnerable to extreme predation (Fegley et al. 2009, Carroll et al. 2010). At this point, the young scallops can be released from the bags into areas with ideal bottom habitat, thus giving them a greater chance of surviving to adulthood and contributing to future year-classes. Martha's Vineyard also uses spat bags to enhance northern bay scallop populations. There, scallops are reared in a hatchery until just after settlement, when they are then placed in spat bag nurseries which are deployed into the natural environment (Robinson et al. 2016).

Although supplies for this method can be relatively low-cost compared with spawner enclosures, given that most areas have low wild bay scallop abundance, hatchery-reared scallops are needed in most situations, which can inflate overall costs. In addition, similar to caged spawner sanctuaries, this method requires significant labor to deploy, maintain, and empty spat bags. The caged spawner sanctuary method has received much more research attention and has shown more success compared with spat bag nurseries, and is thus likely to be a more efficient use of resources where bay scallop restoration is concerned. As a result, spat bag nurseries are presumably best used in combination with spawner sanctuaries, when resources allow, to increase the chances of successful settlement and survival of spawned scallops.

LOCAL CONTEXT

Study Area—Point Judith Pond, RI

The south shore of Rhode Island is characterized by coastal lagoons, locally known as salt ponds. This work is focused on one of the larger salt ponds, Point Judith Pond, which has an area of 6.3 km^2 (Pfeiffer-Herbert 2007). A smaller salt pond, Potter Pond, is connected to Point Judith Pond on the western coast. A narrow channel connects the two, which allows for continuous waterflow. The eastern coast of Point Judith Pond is a primarily residential area, whereas the western coast is primarily undeveloped or rural land (RIDEM 2008). Point Judith Pond is home to the port of Galilee, which represents a major fishing port for Rhode Island, and shellfishing is the primary form of commercial fishing within the pond (RIDEM 2008).

Point Judith Pond is fairly shallow, with an average depth of 0.6 m (RIDEM 2008). The average salinity of the pond is 29; salinity is stabilized throughout the year by the permanent inlet to the Atlantic Ocean, which provides a flushing period of the pond of approximately 2 days (Pfeiffer-Herbert 2007). Historically, the bottom composition of Point Judith Pond was dominated by eelgrass (Huber 2003), which has experienced significant declines throughout the past several decades (Pfeiffer-Herbert 2007). Although restoration efforts between 2009 and 2012 led to a 7.4% increase in overall eelgrass abundance, producing a coverage estimated at 0.41 km^2 (Bradley et al. 2013), eelgrass abundance subsequently decreased by 48% from 2012 to 2016, and the most recent analysis has shown an overall eelgrass cover of only approximately 0.21 km^2 (Bradley et al. 2017).

The Salt Ponds Coalition (SPC), a nonprofit volunteer-based organization, has been monitoring the water quality in Point Judith Pond for many years. The SPC measures dissolved oxygen, chlorophyll a, bacteria, and organic and inorganic nitrogen concentrations at five locations throughout the pond and calculates an aquatic health index based on these factors (Torello & Callender 2013). The monitoring sites in the northern half of Point Judith Pond have shown a general decrease in overall water quality since 2008 and consistently have an aquatic health index of fair to poor water quality (Torello & Callender 2013, SPC 2017, 2018). In particular, the northern half of Point Judith Pond has shown a trend of decreasing dissolved oxygen and increasing nitrogen, along with consistently elevated algae levels (Torello & Callender 2013, SPC 2017, 2018, 2019). In addition, instream waters from the Saugatucket River, which empties into Point Judith Pond, have displayed elevated concentrations of fecal coliform bacteria for the past several decades (RIDEM 2008), and in 2018 the northern portion of Point Judith Pond had an average fecal coliform concentration of 746 MPN/100 ml (SPC 2019). A concentration this high renders shellfish unsuitable for human consumption, and as a result, much of the northern portion of Point Judith Pond is closed to shellfish harvest. However, water quality at the SPC sampling locations in the southern half of Point Judith Pond has remained fair to good since 2008 (Torello & Callender 2013, SPC 2017, 2018). The sampling locations in the lower half of the pond have shown the opposite trends compared with the northern sites, with an increase in dissolved oxygen and decrease in nitrogen from 2015 to 2017 (SPC 2017, 2018).

History of Rhode Island Bay Scallops

The bay scallop has long been an iconic species in Rhode Island. State landings data extends as far back as 1950, when harvests were nearly 180,000 pounds (Baczenski et al. 1979, NOAA 2021). In the 1960s, RI bay scallop populations decreased, and commercial fishery harvests fell to between 1,000 and 4,000 pounds annually (NOAA 2021). Over the past several decades, multiple bay scallop restoration efforts, conducted by several different groups, have been completed in the state (Table 1). In the 1970s, RIDEM initiated a restoration program for bay scallops. At the beginning, approximately 19,000 wild bay scallops were transplanted from Massachusetts to several RI salt ponds, including Point Judith Pond (Sisson 1970, Russell 1973). The RIDEM also established a state-run shellfish hatchery in 1974 to supplement their bay scallop restoration efforts, and over 6,000 scallops from the hatchery were released between 1974 and 1975 (Karlsson 1976). Despite a lack of monitoring results, overall, the 1970s restoration program appeared successful, as annual harvests once again increased and surpassed that of the 1950s.

The fishery peaked in the years following the 1970s RIDEM restoration efforts, when it supported over 600 active, licensed vessels in RI (MacKenzie 2008), and in 1978, 448,700 pounds were harvested for an ex-vessel value of nearly $1.3 million, which equates to approximately $5.6 million in 2022 (NOAA 2021). Unfortunately, the brown tide HABs of 1985 to 1986 once again decimated the population (MacKenzie 2008). In the following years, commercial bay scallop harvests fell to less than 10,000 pounds annually (NOAA 2021), and despite several additional restoration efforts, bay scallop populations have remained too low to support a sustainable fishery. For example, in 1990, RIDEM deployed caged spawner sanctuaries and free planted scallop seed in many of the coastal salt ponds, again including Point Judith Pond, using scallops purchased from a commercial hatchery in Maine (Dinsdale 1991). The caged spawner sanctuaries were composed of mesh bags inside of wire cages that were deployed just off the substrate in sites chosen based on substrate type, vegetation, boat traffic, and past scallop abundance (Dinsdale 1991). Mortality rates for the caged scallops ranged from 2% to 50%; these initial results were considered positive, and it was anticipated that the caged spawners would grow, survive, and reproduce well enough to contribute to the natural population (Dinsdale 1991). Unfortunately, monitoring results of this effort, if recorded, are not available, so it is unknown whether the bay scallop populations in any of the

TABLE 1.

Previous Rhode Island bay scallop restoration efforts.

Years	Lead organization	Location(s)	Restoration strategies used	Results	Source(s)
1969 to 1971	Rhode Island Department of Environmental Management	Narragansett Bay, unspecified coastal salt ponds	Transplanting wild scallops	Qualitative observations suggested acceptable growth and survival of seeded stock; unknown impact on population density or abundance	Sisson (1970) and Russell (1973)
1974 to 1976	Rhode Island Department of Environmental Management	Winnapaug Pond	Free release of hatchery-reared juvenile scallops	1974 trial release was unsuccessful; 1975 release initially considered successful; unknown impact on population density or abundance	Karlsson (1976)
1990 to 1991	Rhode Island Department of Environmental Management	Ninigret Pond, Point Judith Pond, Quonochontaug Pond, Winnapaug Pond	Caged spawner sanctuaries, free release of scallop seed	Growth and mortality rates quantified; unknown impact on population density or abundance	Dinsdale (1991)
2003 to 2008	North Cape Shellfish Restoration Program	Ninigret Pond, Potter Pond, Quonochontaug Pond, Green Hill Pond, Point Judith Pond	Free-planting seed, caged spawner sanctuaries	Quantified increases in bay scallop abundance and settlement in multiple ponds	Hancock et al. (2005, 2006, 2007) and DeAngelis et al. (2008, 2009)
2010 to 2014	Save the Bay	Point Judith Pond, Ninigret Pond	Caged spawner sanctuaries	Quantified increases in bay scallop density in Point Judith Pond and Ninigret Pond	STB (2013, 2014)

stocked ponds exhibited demonstrable increases in the following years due to this effort.

The next bay scallop restoration effort that was conducted in Rhode Island was part of the NCSRP from 2003 to 2008. Initially, this program free-released hatchery-reared juvenile scallops into a variety of coastal salt ponds; however, in 2004, monitoring showed that bay scallop abundance was extremely low, with only approximately 10,000 scallops identified (Hancock et al. 2005). As a result, the program switched to deploying caged spawner sanctuaries, first in Ninigret Pond in 2004 and 2005, followed by Quonochontaug Pond in 2006 and 2007, and finally Point Judith Pond in 2008. This method proved to be more successful at increasing scallop abundance, and although more expensive than direct reseeding, it was found to be a cost-effective method for enhancing scallop recruitment (Hancock et al. 2005, 2006, 2007, DeAngelis et al. 2008, 2009). The enclosures used were wire mesh cages, separated into four tiers, in which hatchery-reared adult scallops were placed (Hancock et al. 2005, 2006, 2007, DeAngelis et al. 2008, 2009). In each pond, cages were deployed in shallow areas chosen based on habitat, flow dynamics, historical scallop abundance, and boat traffic (Hancock et al. 2005, 2006, 2007, DeAngelis et al. 2008, 2009). In 2008, 20,500 adult bay scallops were deployed in cages in Point Judith Pond (DeAngelis et al. 2009). The scallops were originally reared and over-wintered as juveniles in aquaculture gear in the adjacent Potter Pond (DeAngelis et al. 2009). Although 2008 was the final year of restoration efforts for the NCSRP, monitoring was conducted in 2009 to assess the impact of the Point Judith Pond spawner sanctuaries. Despite funding constraints that kept the monitoring to a minimum, these efforts were able to document an increase in scallop abundance that surpassed 300% in some areas (NCSRP, unpublished data). Overall, the NCSRP was able to successfully increase scallop abundance in multiple salt ponds, including Point Judith Pond, throughout the duration of the program; however, natural bay scallop populations were apparently unsustainable in the long-run, as restoration efforts were resumed in 2010 by STB.

Save the Bay initially re-established caged spawner sanctuaries in Point Judith Pond, followed by Ninigret Pond. Adult scallops were obtained from hatcheries in New York, RI, or Massachusetts (STB 2013, 2014). In Point Judith Pond, 20,000 scallops were deployed in spawning cages in 2010, and an additional 11,000 were deployed in 2011 (STB 2013, 2014). Monitoring was conducted in Point Judith Pond to evaluate the impact of the spawner sanctuaries; although abundance was not determined, the density of scallops in surveyed areas of Point Judith Pond increased from 0.019 scallops/m^2 to 0.0446 scallops/m^2 in 2013 (STB 2013, 2014).

Despite short-term increases in bay scallop populations following individual restoration efforts, overall Rhode Island bay scallop restoration has been of limited long-term success. The limits to the long-term success of these operations are largely related to the stressors described above. For example, as mentioned, the northern half of Point Judith Pond has experienced increasingly impaired water quality, and seagrass habitat in the pond has decreased in recent decades, which likely contributes to keeping bay scallop populations too low to be self-sustaining. Recruitment limitation is also likely a key factor given the very low existing bay scallop population levels. The flowrate and flushing period of the salt pond likely also further inhibits recruitment, as the flushing period in many lower sections of Point Judith Pond is much shorter than the time bay scallop larvae require to enter metamorphosis (approximately 2 wk). This keeps natural recruitment low by causing many larvae to be lost from the system prior to settlement (Pfeiffer-Herbert 2007).

There is still an active commercial quota for bay scallops in Rhode Island, although harvest in recent years has been negligible. Commercial harvest is limited to three bushels per vessel per day from November through December, with dredging for bay scallops only allowed during the month of December and dip-netting allowed throughout the commercial season (Rhode Island Department of State (RIDS) 2022). Since 2006, however, less than three vessels have harvested bay scallops commercially each year (landings data is confidential), except for 2012 when six vessels participated and harvested approximately 300 pounds total (RIDEM, unpublished data). Recreational harvest is permitted to state residents only, with a limit of one bushel per person per day, however recreational harvest data is unavailable (RIDS 2022). As described previously, adult bay scallops that have already spawned will be removed from the population whether it is due to natural mortality or fishery removal, so it is unlikely that this minimal harvest in recent years has had a large impact on the population status of bay scallops in Point Judith Pond.

A state-run shellfish survey recently found that bay scallops were present in extraordinarily small numbers; although this survey did not specifically target bay scallops, between 2016 and 2020, only two bay scallops were identified in Point Judith Pond through this survey (RIDEM, unpublished data). In 2020, however, RIDEM and the University of Rhode Island Graduate School of Oceanography (URI GSO) initiated a new survey to target and more directly assess the distribution and abundance of bay scallops in Point Judith Pond. The methods used in that survey consist of both dive transect surveys and image data collection using two stereo cameras (12-megapixel Prosilica cameras with a 60-degree field of view) and a strobe light for illumination. Visual surveys have been shown to produce higher, and likely more accurate, estimates of bay scallop densities compared with dredging, and are also less invasive (Lyon et al. 2022). An adaptive sampling design was selected for the RIDEM and URI GSO bay scallop survey due to their tendency to cluster within areas of submerged aquatic vegetation (SAV), which has been shown to be more effective in the assessment of fisheries populations for clustering species (Woodby 1998). Fifteen randomly selected plots within the eelgrass habitat of Point Judith Pond were surveyed over 25 m^2 of bottom. The 25 m transect line delineates two parallel 25 m by 1 m transects adjacent to each other. Within each square meter of each transect, the number of live scallops is recorded and their length(s) are collected. In addition, the estimated percent eelgrass, presence/absence of algae, sediment type (e.g., mud, silt, sand, or cobble), presence of predators and any empty scallop shells, and water quality (i.e., temperature, salinity, and dissolved oxygen) are recorded at each transect station. Given that this collaborative survey targets bay scallops and has documented the species in higher numbers than the previous state-run shellfish survey, this has sparked the opportunity to resume bay scallop restoration efforts in Point Judith Pond. For example, this survey will provide baseline data on bay scallop abundance, distribution, size class (year 1 or 2), density, predator abundance, and habitat type that is necessary prior to implementing any additional restoration efforts. In addition, a continuation of this survey will also provide monitoring that will be needed during and post-restoration to identify any changes in bay scallop populations over time.

POINT JUDITH POND BAY SCALLOP HABITAT SUITABILITY INDEX

Methods

A pressing issue for the success of bay scallop restoration is the selection of the most suitable sites for restoration activities. Many of the factors that should be considered when choosing a site and strategy for bay scallop restoration have been described above, including environmental parameters suitable for bay scallop growth and survival, as well as threats and stressors to bay scallop populations. Given these considerations, a habitat suitability index map of Point Judith Pond was created to highlight sites that are likely to yield the most successful restoration results by overlaying datasets and maps of relevant information in ESRI ArcGIS. To identify suitable sites for bay scallop restoration within Point Judith Pond, an exclusionary assessment was first conducted. First, navigation channels from the NOAA Office of Coast Survey (NOAA, n.d.) and areas leased for aquaculture were excluded, as these areas are deemed prohibitive for restoration due to conflicting human-uses. Next, shellfish closure areas were excluded from the index; these areas are primarily where water quality is poor and therefore likely unsuitable for bay scallop growth, and because shellfish harvesting is prohibited, any surviving scallops would be unsuitable for harvest. Shapefiles of leased aquaculture and shellfish closure areas were downloaded from the RIDEM Marine Fisheries Maps web portal (RIDEM 2021a).

Available data on environmental and habitat characteristics for Point Judith Pond were then evaluated to determine the most important factors that are likely to influence the suitability of areas for bay scallops in the pond. First, the depth distribution of Point Judith Pond was mapped using the University of Rhode Island (URI) Topobathy Digital Elevation Model (URI 2016). No areas reached depths that are prohibitive to bay scallop growth and survival, so this factor was not considered further. Unfortunately, fine-scale environmental data from locations throughout the pond and all months of the year that could be reliably spatially interpolated were not readily available for inclusion in this habitat suitability index. In an effort to gain some insight into variable environmental conditions, available data on the minimum and maximum water temperature and salinity from May through October at RIDEM 2010 to 2020 (RIDEM 2021b) and Watershed Watch 2011 to 2020 (URI 2021) water sampling stations were plotted. Although this data likely does not include the most extreme temperature and salinity values that occur in Point Judith Pond (i.e., the lowest temperatures are expected to occur in the winter months) the timeframe of this data does include the spawning season. The recorded temperature minimums and maximums for May through October did not vary greatly among the sampling stations throughout the pond. Salinity varied slightly more; although salinity in the northern area of Point Judith Pond fall too low to be suitable for bay scallop growth and survival, this portion of the pond was already excluded due to shellfish closure regulations. However, salinity ranges did not differ greatly in the southern portion of Point Judith Pond and thus had minimal impact on the overall selection of suitable sites for bay scallop restoration. As a result of data constraints, temperature and salinity were also not included in the final habitat suitability index.

Submerged aquatic vegetation cover in Point Judith Pond was then mapped using percent coverage from the United States Department of Agriculture (USDA) Natural Resources Conservation Service subaqueous soil surveys (USDA 2019) as well as the merged aerial identification of SAV present in 2009, 2012, and 2016 (Rhode Island Geographic Information System 2017). Given the importance of SAV such as eelgrass for bay scallop settlement and survival, as well as the varied distribution of SAV cover throughout the pond, this factor was included in the final habitat suitability index. Next, the distribution of substrate types throughout Point Judith Pond was mapped (USDA 2019). Bottom substrate type in Point Judith Pond ranges from fine fluid silt to boulder–cobble. Large areas, particularly in the inner pond, are dominated by fluid silt which is not suitable for bay scallop feeding, growth, and survival. As a result, areas with this substrate type were excluded from further consideration. However, many coastal areas along the edges of the pond were found to contain more coarse substrates that would provide appropriate habitat for bay scallops. These substrate types were combined as "firm soils" for use in the suitability index. Historical data on bay scallop distribution and density within the pond (United States Environmental Protection Agency 1974, Baczenski et al., 1979), as well as locations used for spawner sanctuaries in

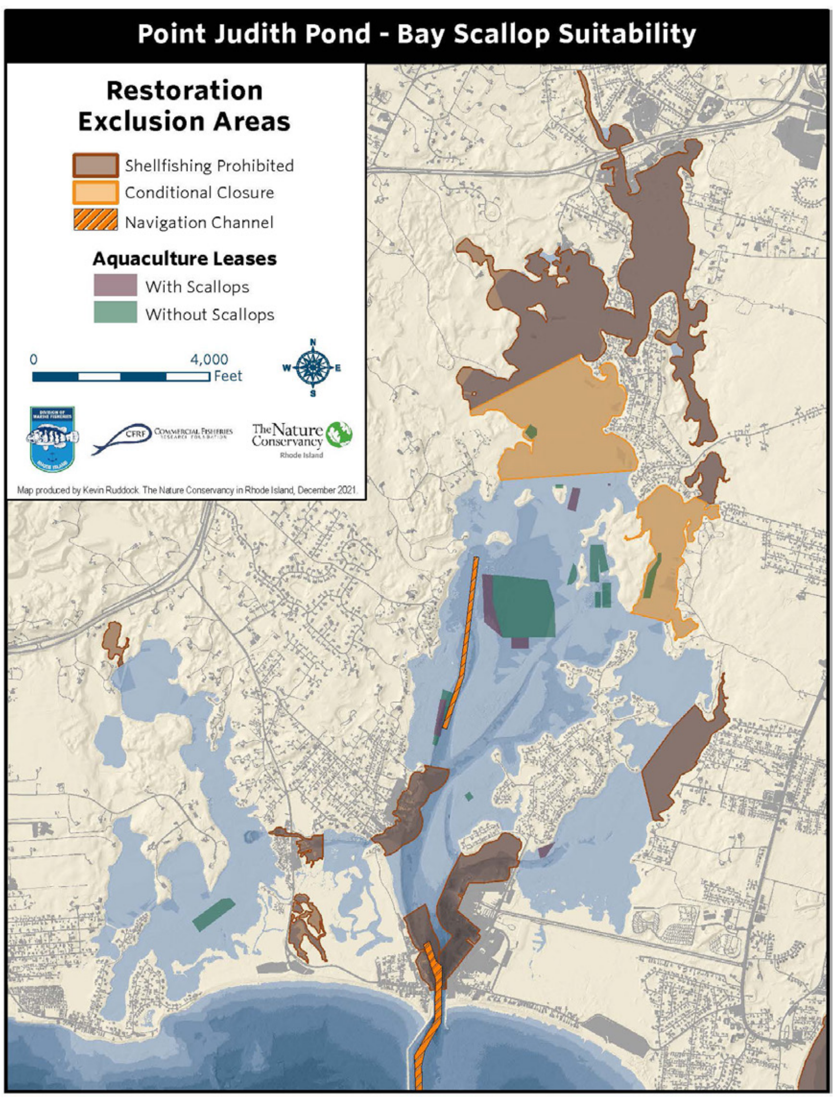

Figure 1. Detailed mapping results of factors used in the exclusionary assessment for bay scallop restoration sites in Point Judith Pond.

previous restoration efforts (Sisson 1970, Dinsdale 1991, STB 2013, 2014), were also collated and mapped to identify locations that historically supported bay scallops and thus may be suitable for future restoration efforts.

Finally, a habitat suitability index was created by ranking areas through Point Judith Pond from a score of 0 (not suitable) to 6 (highly suitable). Sites were first given a score ranging from 1 to 3 based on SAV percent cover from subaqueous soils (0.2%–8% = 1 point; 9%–28% = 2 points; >29% = 3 points). A maximum of one point was added to sites that also had SAV present from aerial interpretation in any year of aerial assessment. An additional point was added to sites that had historical scallop beds present, and one final point was added for areas with firm (nonfluid) subaqueous soils. The locations of previous spawner sanctuaries were then overlaid with the ranked areas to provide additional insight on potential sites for future restoration efforts. Finally, the excluded areas (shellfish closure areas, navigation channels, aquaculture leases, and areas characterized by fluid soils) were masked over the ranked areas. This was done so that the underlying ranked scores in these areas are still visible, and future restoration programs can weigh the pros and cons of conducting restoration in some of these locations depending on the goals of the program.

As mentioned previously, RIDEM and URI GSO are currently conducting annual surveys of bay scallops in Point Judith Pond, and this provided the opportunity to preliminarily assess the performance of the habitat suitability index by comparing the ranked sites to the density of bay scallops from the first 2 y of this survey. As such, the habitat suitability index was overlaid with 2020 and 2021 density data from the RIDEM/URI GSO transect survey.

Results

The exclusionary assessment indicated large portions of Point Judith Pond are likely prohibitive to bay scallop restoration efforts (Fig. 1). The depth distribution of Point Judith Pond remains shallow throughout; with the exception of navigation channels, the majority of the pond is less than 10 feet deep (Fig. 2). Water temperature minimums and maximums remain mostly similar throughout the pond, ranging from a minimum of 9°C up to 27°C throughout the months sampled in

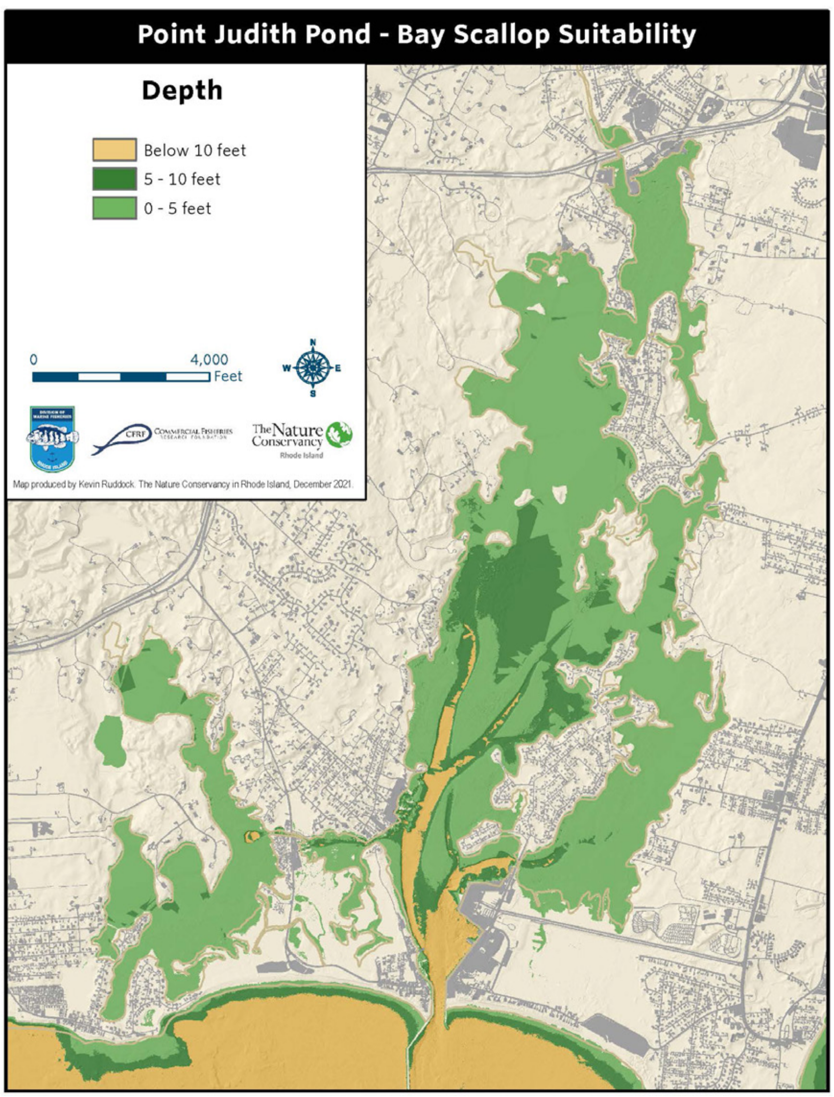

Figure 2. Depth distribution of Point Judith Pond.

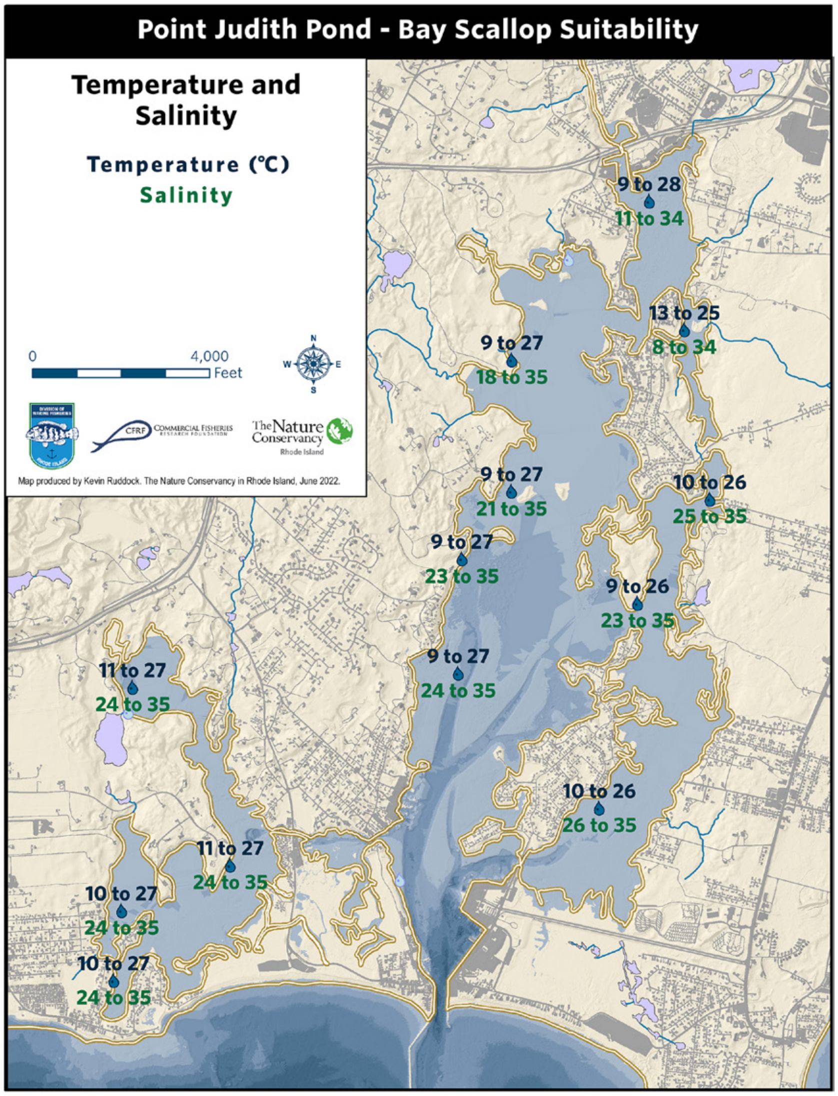

Figure 3. Temperature and salinity ranges for locations throughout Point Judith Pond.

that dataset (Fig. 3). Salinity remains fairly high in the southern portion of the pond (range: 24–35) and decreases to as low as a salinity of eight in the northern reaches of the pond, where the Saugatucket River empties into the salt pond (Fig. 3).

Although overall SAV cover of Point Judith Pond has decreased over the past decade, several areas in the middle and lower portions of the pond have consistently had a minimum eelgrass cover of 16%–32%, and these areas would likely provide adequate settlement substrate for young scallops in most need of protection from predators (Fig. 4). In addition, several areas that historically supported bay scallop populations were identified throughout the pond, and the locations of spawner sanctuaries deployed during previous restoration efforts by RIDEM, the NCSRP, and STB were mapped to provide additional guidance on site selection (Fig. 4). The distribution of bottom substrate types in Point Judith Pond is shown in Figure 5. The final habitat suitability index, which ranked locations on a scale from zero (not suitable) to six (highly suitable), illustrates that locations throughout the pond vary in how likely they are to be suitable for bay scallops (Fig. 6). It is important to note that less than 1% of the pond was ranked with the highest possible score, and the majority of the pond had a score of two (Table 2). In general, scallops in the RIDEM/URI GSO scallop survey were not found in areas that were considered not suitable or of low suitability by the index, and several locations with the highest density of scallops were in areas with at least medium suitability rankings (Fig. 7).

DISCUSSION

The habitat suitability index created here ranked sites throughout Point Judith Pond based on how likely they are to provide the appropriate environmental and habitat characteristics to promote bay scallop growth and survival given currently available data. Unfortunately, less than 1% of sites were ranked with the highest possible score of six. Given the evidence of a loss of eelgrass habitat in recent years, as well as decreasing water quality in large portions of the pond, described above, it is not surprising that the majority of Point Judith Pond is likely not highly suitable for bay scallops. Despite this, several areas of the pond were ranked as having medium suitability, and it is possible that areas with scores of three or greater will

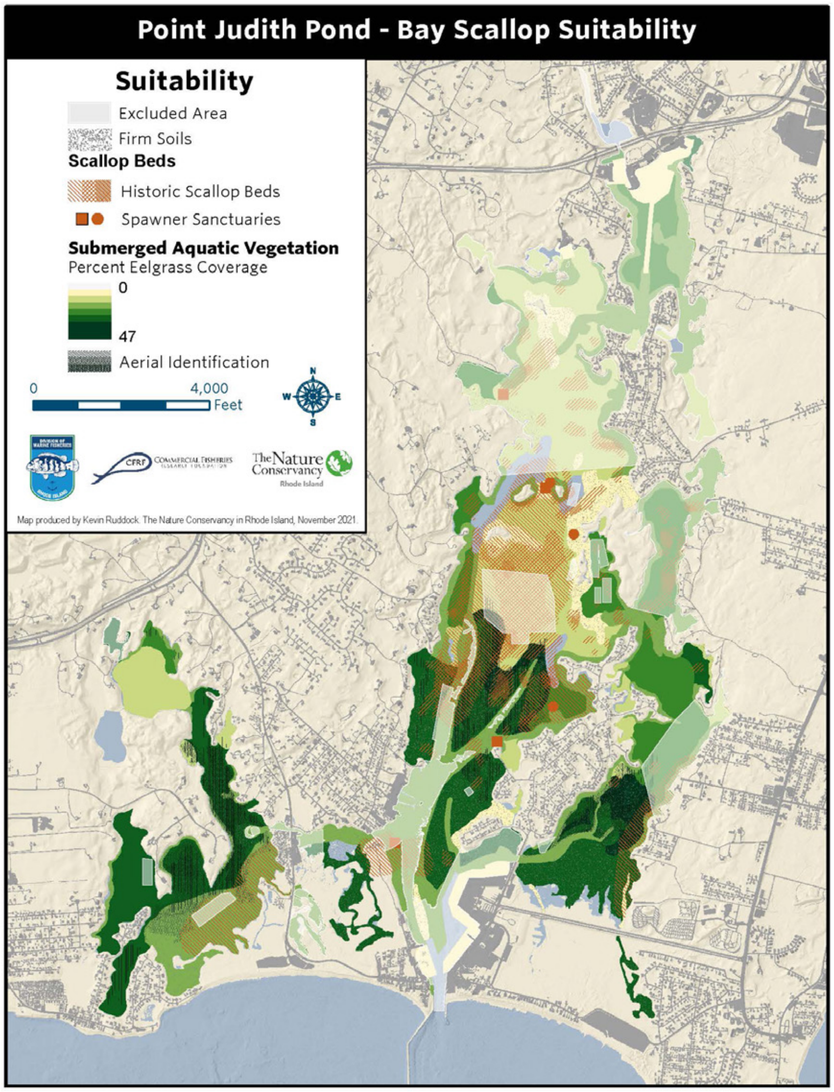

Figure 4. Submerged aquatic vegetation cover, historic scallop beds, and the locations of previous bay scallop spawner sanctuaries in Point Judith Pond. Excluded areas are transparent.

provide adequate habitat for bay scallops. In addition, although no strong conclusions can be drawn, the preliminary qualitative comparison of the index with the RIDEM/URI GSO scallop survey data suggests a level of confidence can be given to the habitat suitability index in identifying sites that are most likely to support bay scallops in Point Judith Pond. Further monitoring will provide the opportunity for a more thorough comparison between bay scallop density and the habitat suitability index results, which could be used to quantitatively validate the model.

The habitat suitability index was created to be used as a guide for future restoration planning to help identify where to focus renewed bay scallop restoration efforts in Point Judith Pond. In general, higher ranked sites should be prioritized in these future efforts to increase the chances of successful restoration, and avoiding sites that have been ranked as not suitable will help maximize the efficiency of such efforts. Due to the difficulties in establishing sustained, long-term increases in bay scallop populations in Point Judith Pond in the past, a combination of the restoration strategies described previously is likely needed to enhance the bay scallop population, similar to the approach used in Nantucket (Herr et al. 2012). As different restoration strategies have additional considerations for choosing the most suitable sites, the habitat suitability index can be used in combination with the additional detailed habitat characteristics maps provided here to select the most appropriate sites for each strategy.

As previously discussed, caged spawner sanctuaries represent the most widely used and successful restoration strategy for bay scallops, and it is recommended that this strategy to be part of any future restoration efforts for bay scallops in Rhode Island. Caged spawner sanctuaries have been used in the past to produce increases in bay scallop abundance and/or density in Point Judith Pond in the short term (NCSRP, unpublished data; STB 2013, 2014). Sustained annual or biannual deployments of caged broodstock are thus likely to result in similar increases over a longer period of time, which could allow the natural bay scallop population to increase to a level that is less susceptible to once again crashing due to natural and anthropogenic stressors. The index can be used as a general guide to find potential

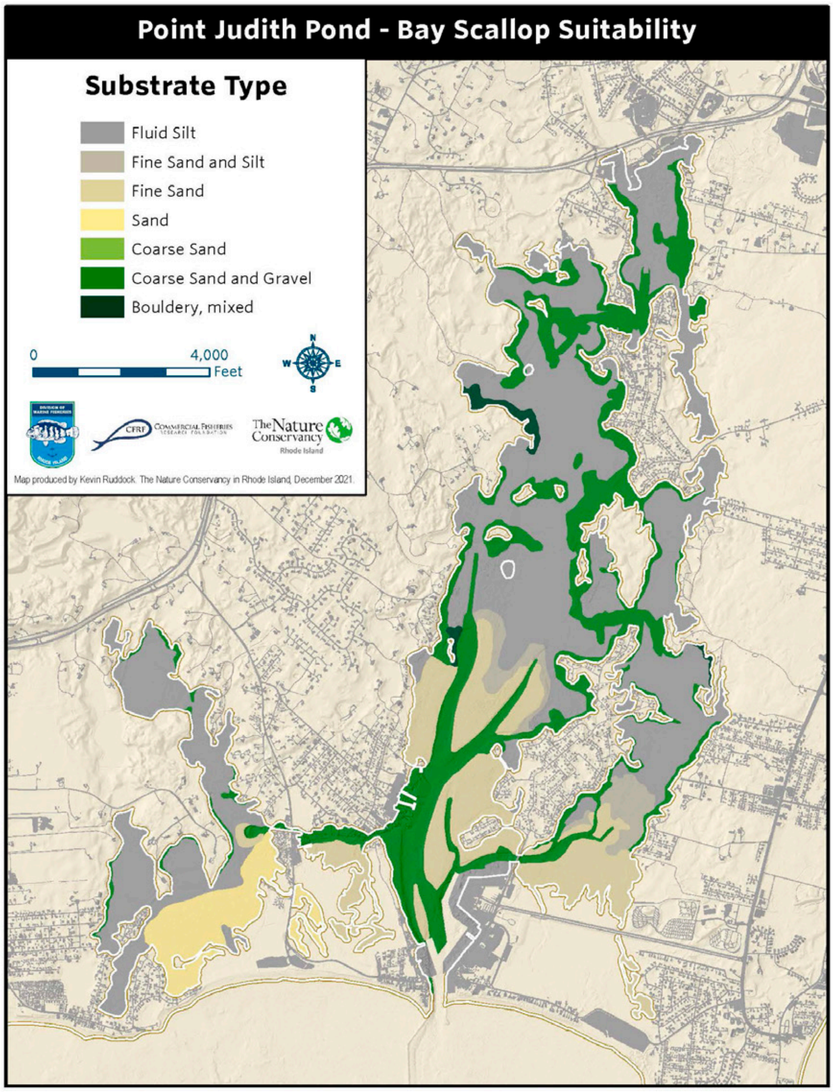

Figure 5. Distribution of bottom substrate types throughout Point Judith Pond.

locations for spawner sanctuaries by narrowing down potential sites based on ranked scores, whereas additional details on individual factors can be used to refine site selection even further. For example, the habitat suitability index indicates several locations throughout Point Judith Pond are likely to have suitable habitat for bay scallops. Spawner sanctuaries are generally best sited in at least partially enclosed areas with protection from high flow rates and gravely bottom structure (Fig. 5; Hancock et al. 2006, Kirk et al. 2020), so these specific criteria can be used to select the most appropriate site from among all potentially suitable sites identified by the index. In addition, because previous restoration programs were able to demonstrate success using spawner sanctuaries in specific locations throughout the pond chosen based on extensive research and consideration (DeAngelis et al. 2008, STB 2013, 2014), selecting these sites that are also located in areas that have higher index scores may increase the chances of a successful restoration program.

In addition, the free release of competent larvae or newly settled spat has been shown to be a lower-cost strategy that can act as an efficient supplement to spawner sanctuaries (Leverone et al. 2010, Herr et al. 2012). In Point Judith Pond, this method could help overcome the loss of larvae from the system during their 2-wk pelagic phase and provide the opportunity for more individual scallops to successfully settle within the salt pond. For this strategy, there should be particular emphasis on choosing suitable sites with dense and consistent SAV cover (Figs. 4 and 5). As previously discussed, eelgrass is particularly important for early life-stages that are most susceptible to predation, so this specific factor should be prioritized when identifying sites for this strategy (Carroll et al. 2022). A restoration plan that accounts for the transplantation of seed that has settled in areas that are considered not suitable or of low suitability by the index to locations with higher suitability rankings could also be a beneficial restoration strategy in Point Judith Pond.

It has been demonstrated that the bay scallop habitat suitability index and habitat characteristics maps created herein have direct applicability to the planning of renewed restoration efforts for bay scallops in Point Judith Pond, RI. As restoration programs are implemented, it is important to adapt plans as needed given available data and resources (Stern et al. 2011). Such adaptive management of restoration helps ensure that the goals of a restoration program are reached in an efficient

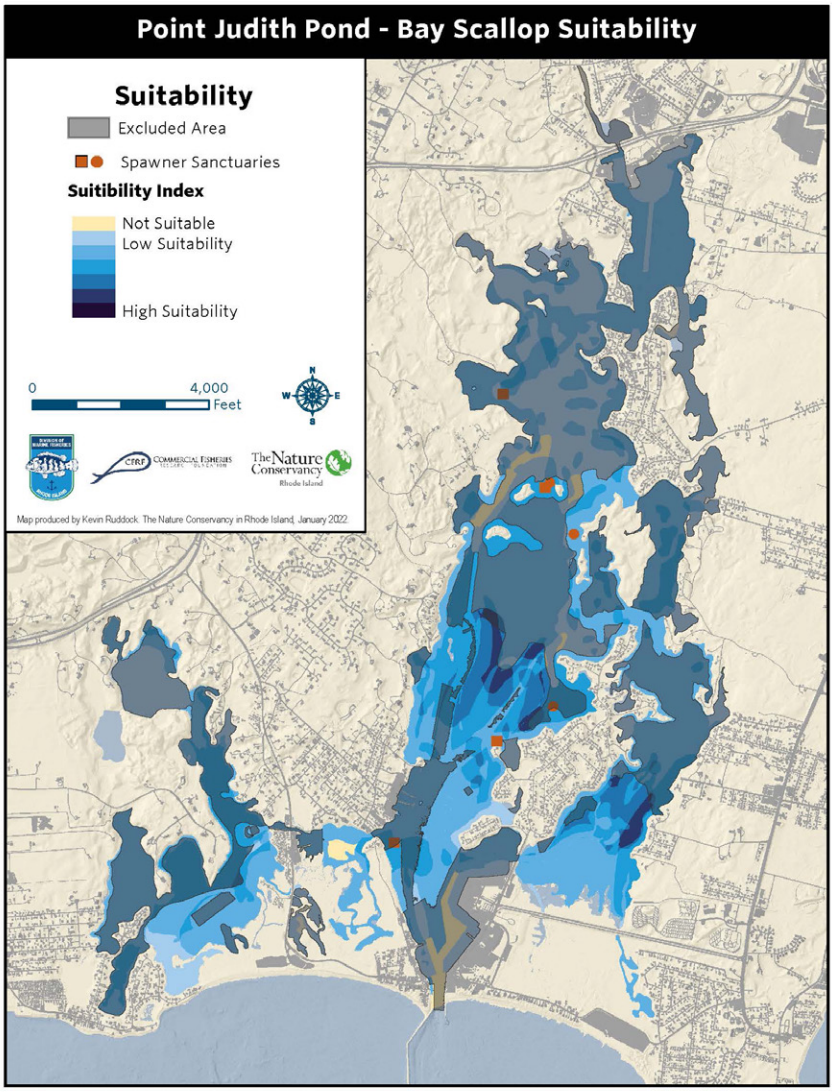

Figure 6. Bay scallop habitat suitability index for Point Judith Pond.

manner (Stern et al. 2011). For example, the habitat suitability index created here represents the locations considered to be most likely to result in successful restoration of bay scallops in Point Judith Pond given the available data on current conditions in Point Judith Pond at the time of writing. As new scientific information becomes available, or conditions change in a way that alters the sites best suited for restoration, it is recommended that restoration planning be modified accordingly to ensure any restoration efforts produce the greatest possible impacts.

Research Recommendations

The bay scallop habitat suitability map created here was produced using a combination of relevant and readily available

TABLE 2.

Area and percentage of Point Judith Pond that were ranked as each possible score in the habitat suitability index.

	Area of Point Judith Pond (hectares)			Percent of Point Judith Pond		
Index score	Not excluded	Excluded	Total	Not excluded	Excluded	Total
0	2.027	31.302	33.330	0.2	3.9	4.1
1	14.945	152.307	167.248	1.8	18.8	20.6
2	144.938	278.286	423.224	17.9	34.3	52.2
3	74.964	73.786	148.750	9.3	9.1	18.4
4	25.163	2.606	27.774	3.1	0.3	3.4
5	9.000	0.987	9.988	1.1	0.1	1.2
6	0.004	0.000	0.004	0.0	0.0	0.0

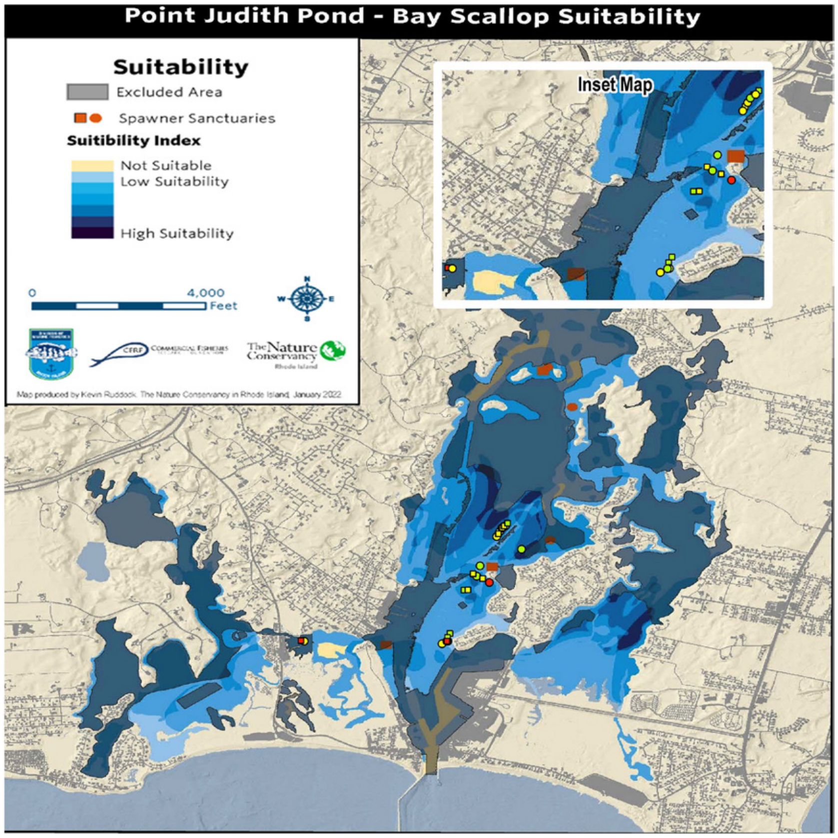

Figure 7. Bay scallop habitat suitability index overlaid with bay scallop density data from the Rhode Island Department of Environmental Management and University of Rhode Island Graduate School of Oceanography bay scallop survey. Squares represent 2021 data, whereas circles represent 2020. Red indicates a density of 0 scallop/m2; yellow a density between 0 and 0.1 scallop/m2; and green a density greater than 0.1 scallop/m2. The inset map represents a zoomed in view of the area that was surveyed.

data sources. Information on a number of additional factors would help refine site selection even further and ultimately make restoration projects as effective as possible. As such, four further avenues of research are recommended, as the results of such studies could be used to help improve site selection for bay scallop restoration and ensure that restoration efforts have the greatest possible chance of success.

The first recommendation is to create a more detailed benthic habitat map of Point Judith Pond. Up to date, fine-scale information on the current benthic structure of Point Judith Pond is currently lacking. As described previously, bay scallops require benthic substrate to settle on and to provide protection from predators. The habitat suitability maps in this document use data on SAV cover and substrate/soil type from several different data sources, some of which are nearly a decade old. In addition, there is no mapping data available on the distribution of other sources of benthic substrate that bay scallops could use for settlement in the absence of eelgrass. Updated and comprehensive data on the fine-scale features of the benthic area of Point Judith Pond would thus greatly assist in refining the release locations of bay scallops.

The second recommended research avenue is to create a larval transport model for Point Judith Pond. For a healthy, sustainable bay scallop population, larvae must remain within the system through their pelagic phase, and not disperse to the open ocean, until settlement. In addition, to maximize the chances of survival post-settlement, larvae need to be transported to areas with appropriate habitat characteristics. As a result, the circulation patterns that affect the dispersal of larvae in the system should be understood to identify sites for larval release and/or spawner sanctuaries that would maximize the amount of time pelagic larvae remain within the pond and increase the chances of settlement in areas with suitable habitat (Liu et al. 2015, McManus et al. 2019). For example, a high-resolution, three-dimensional hydrodynamic larval transport model for Buzzards Bay, MA was able to identify spawning locations that are most likely to produce bay scallop larvae that will settle in areas with adequate habitat (Liu et al. 2015). In addition, larval transport models can help identify the extent to which larvae spawned from a system of interest are lost to the population, as was done for northern quahogs (*Mercenaria mercenaria*) in Narragansett Bay, RI (McManus et al. 2019). Although a basic hydrodynamic model has been created for Point Judith Pond in the context of winter flounder (*Pseudopleuronectes americanus*) larval transport, that study was conducted nearly four decades ago and was restricted to two-dimensional modeling (Crawford & Carey 1985). As a result, an updated, three-dimensional hydrodynamic-transport model for Point Judith Pond would thus be extremely useful for refining bay scallop restoration sites and corresponding site-specific strategies.

In addition, the detailed mapping of bay scallop predators in Point Judith Pond would be beneficial. As mentioned previously, predation is one of the main sources of bay scallop mortality. Currently, detailed information on the abundance, distribution, seasonal dynamics, and density of bay scallop predators in Point Judith Pond is not available. Although the presence of bay scallop predators is recorded as part of the ongoing RIDEM/URI GSO survey, that survey does not cover all locations throughout Point Judith Pond. Gaining a better understanding of where, when, and in what numbers bay scallop predator species occur in Point Judith Pond would thus lead to improved site selection for bay scallop restoration and likely result in increased survival (Schmitt et al. 2016, Carroll et al. 2022).

Finally, consistent and expanded long-term monitoring of bay scallops in Point Judith Pond is important to assess the population in relation to habitat characteristics over time and to help further validate the habitat suitability index. For example, given the extensive evidence suggesting eelgrass as the preferred habitat of bay scallops, this factor was heavily weighted in the current habitat suitability index. If monitoring shows that bay scallops in Point Judith Pond are equally or preferentially found in areas with alternative substrate types, however, the index should be updated to reflect this information. In addition, it is important to gain additional insight into how the index relates to the presence or density of bay scallops in a given area to quantitatively validate the index.

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