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Modeling ecological carrying capacity of shellfish aquaculture in highly flushed temperate lagoons

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ABSTRACT

Lagoons are some of the most productive systems on the planet — not only for aquaculture, but for fisheries, recreation, and as nurseries for many important species. These systems are also highly susceptible to degradation. Aquaculture is a rapidly increasing industry capable of impacting these sensitive systems. Dense human populations and intensive multiple uses of ecologically sensitive coastal waters have forced resource managers to evaluate the impact of expanding shellfish aquaculture to ensure sustainable development. A mass-balance ecosystem model of highly flushed temperate lagoons in Rhode Island, USA was constructed to calculate the ecological carrying capacity for shellfish aquaculture. Cultured oyster biomass is currently 12 t km^{-2} live weight and could be increased to 62 times this value before exceeding the ecological carrying capacity of 722 t km^{-2}. The lagoons were found to be a detritus-dominated system with high energy throughput which may permit the high capacity of the system for additional shellfish biomass allowing managers to consider expansion of shellfish aquaculture to densities much higher than comparatively oligotrophic systems could support. Managing by ecological carrying capacity follows an Ecological Approach to Aquaculture by maintaining ecological integrity and the sustainability of the aquaculture industry as well as other human uses of the lagoon system.

1. Introduction

Coastal lagoons are inland shallow water bodies connected to the ocean by an inlet (Kjerfve, 1994). High productivity of estuarine lagoons supports myriad biological process and human uses (Kjerfve, 1994; Mann, 2000; Nixon, 1982). Proximity to shore, shallow depth and protected shorelines make most lagoon systems accessible to humans and susceptible to anthropogenic degradation.

Of the many human uses and industries dependent on healthy lagoon systems, aquaculture deserves notable attention. Success of a shellfish aquaculture industry is dependent on high productivity of lagoon systems. Cultured shellfish feed on ambient plankton and detritus, requiring no inputs of feeds, drugs or fertilizers. Shellfish farms are directly linked to the greater lagoon-wide system and do not operate independently of natural ecosystem processes and conditions. While it is widely recognized that shellfish aquaculture provides many positive ecosystem services, there is a point where an excessive biomass of cultured shellfish can be predicted to threaten the ecological integrity of the ecosystem.

Bivalve aquaculture is increasing at a rapid rate in concentrated areas around the world (Costa-Pierce, 2008; Costa-Pierce et al., 2010; FAO, 2009) and has a long history in estuarine lagoons (Kurlansky, 2006; Valiela, 2006). Unearthed oystermiddens in the Northestern U.S. dating back to the 1600s are evidence of substantial wild harvests from coastal waters (Kurlansky, 2006). Substantial harvests in Rhode Island (RI) lagoons continued into the 1950s from wild and cultivated oysters until breachways were stabilized (Lee, 1980). Breachways were constructed with the purpose of improving the shellfish industry by increasing flushing and salinity (Lee, 1980). Stabilized breachways did alleviate symptoms of stagnation and eutrophication but also had many adverse effects including: loss of brackish water fisheries, increased sedimentation, and changes in species composition (Lee, 1980). Human use of the RI coastal environments has increased dramatically in recent decades. An increased number of septic systems along with a series of severe storm events most likely led to the permanent decline of the shellfishery (Lee, 1980). Today natural populations of bay scallops and oysters exist in small isolated patches through heavily monitored and maintained restoration efforts (DeAngelis et al., 2008; Hancock, et al., 2007). Rhode Island lagoons are subject to cumulative anthropogenic impacts which have greatly

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altered the system, nutrient regimes, sediment geochemistry, and the delicate balance of the many species that rely on this habitat (Lee, 1980).

Today, the cultivated oyster industry has effectively eclipsed the wild harvest production industry on account of its decline. While a thriving wild harvest clam industry still exists, oysters (*Crassostrea-virginica*) make up 99% of the aquaculture in the state. In fact, the aquaculture industry has been doing extremely well in recent years and has increased from a $130,000 to a $1,600,000 industry in only six years, effectively doubling the space utilized for the industry to 28 farms or 50 ha statewide. Half of the state's aquaculture is in lagoons (Alves, 2007). On a global scale, this industry is still quite small. However, the lagoons are also quite small ranging from 0.72 to 7.85km^2 and located in the smallest and second most densely populated state in the USA. As such, the rapid rate of increase is quite notable to commercial clam harvesters and other users of the lagoons. Aquaculture is only one of several industries and recreational uses of this area. It is in the best interest of all users to mitigate user conflicts and maintain ecological integrity.

Proper management is prudent to avoid perturbations of these delicate, heavily used and ecologically important systems. An Ecological Approach to Aquaculture (EAA) is one way to preserve the anthropogenic and ecological resources of this system (Soto, 2010). An EAA is guided by three principles: "aquaculture is developed in the context of ecosystem functions and services with no degradation of these beyond their resilience capacity, aquaculture should improve human-wellbeing and equity for all relevant stakeholders, and aquaculture should be developed in the context of other relevant sectors" (Soto, 2010). EAA acknowledges equity among human uses while maintaining ecological sustainability.

An EAA can be applied using carrying capacity. Carrying capacity has been adapted into four types of carrying capacity appropriate for bivalve aquaculture (Inglis et al., 2002):

1. Physical — "total area of marine farms that can be accommodated in the available physical space",
2. Production — "the stocking density of bivalves at which harvests are maximized",
3. Ecological — "the stocking or farm density which causes unacceptable ecological impacts",
4. Social — "the level of farm development that causes unacceptable social impacts."

While physical and production carrying capacity are useful on a farm-scale, acknowledging that the farm is only a part of a larger ecosystem requires consideration of ecological and social carrying capacities. In order to take an ecological approach to aquaculture (Soto, 2010), it is helpful to consider ecological carrying capacity.

Both the ecological and social carrying capacities are defined by the acceptability of change and, therefore, depend on social values (McKindsey et al., 2006). McKindsey et al. (2006) explained that society defines the variables of interest and how much those variables can change. Therefore, society has a part in defining acceptability. Society can determine the acceptability of alterations to sustained ecological function, species biomasses and energy flows between trophic levels. Stakeholders in RI wanted to calculate carrying capacity ofbivalve aquaculture for current ecosystem conditions and were therefore, unwilling to accept any substantial change in ecosystem function, biomasses, or energy flows (Byron et al., 2011). After the goals and definition of carrying capacity are clarified, ecological carrying capacity can be calculated using mass-balance modeling (Byron et al., 2011; Jiang and Gibbs, 2005; McKindsey et al., 2006).

1.1. Modeling

Ecopath is a static, mass-balance ecosystem-based modeling software that focuses on energy transfer between trophic levels and is widely used in fisheries management (www.ecopath.org). Ecopath has been used for modeling a wide range of systems and management scenarios (Christensen, 1995; Christensen and Pauly, 1993; Monaco and Ulanowicz, 1997; Vasconcellos et al., 1997) including the carrying capacity of bivalve aquaculture (Jiang and Gibbs, 2005). It differs from most other modeling approaches because it incorporates the full trophic spectrum, which is what makes it truly an ecosystem model appropriate for ecosystem-based management and determining ecological carrying capacity. Conversely, models of production carrying capacity are most applicable at the farm-scale and do not necessarily include all trophic levels (Bacher et al., 1998; Carver and Mallet, 1990; Nunes et al., 2003; Raillard and Ménesguen, 1994). This approach is useful for determining production potential on a farm but is shortsighted for ecosystem management where several user groups depend on the stability and sustainability of the entire system. Furthermore, Ecopath provides a methodology to standardize model outputs, thereby making it easy to compare across systems. Overall, Ecopath is a good balance between simplicity and the complexity of other ecosystem models.

Since Ecopath is a static model, its complexity is limited compared to dynamic models that are capable of tracking variability in fluxes across different temporal and spatial scales. Some critics may view the static nature of Ecopath as a limitation. However, in circumstances where long-term data sets are not available or data are disparate, Ecopath provides a standardized methodology for developing a model. As data improve over time, Ecopath can be expanded to Ecosim and Ecospace which are capable of tracking fluxes over time and space, respectfully.

Ecopath, like any model, does not come without shortfalls and limitations (Plagányi and Butterworth, 2004). Most shortcomings are attributed to user error such as uncritical use of Ecopath default settings — not all species groups should be treated equally even though the default settings are the same (Plagányi, 2007). For example, the default value for unassimilated consumption is 0.2 which underestimates egestion for herbivores and detritivores. A more reasonable rate for these groups would be 0.4 (Christensen et al., 2005). Ecopath settings used in this model are further described in the Model considerations section of the Materials and methods. Perhaps the most unavoidable shortfall of any ecosystem model is the quantity and quality of data available to feed the model. This study attempted to minimize this shortfall by using data collected at the model locations to calculate input parameters and by employing a series of diagnostic tests (Link, 2010) that were used to evaluate data parameterization and will flag areas of data weakness that may need further investigation prior to model balancing.

2. Materials and methods

2.1. Study area

A string of nine barrier beach lagoons line the southern shore of Rhode Island (W71°30′ N41°15′). The ecology and natural history of these lagoons have been described extensively by others since the 1940s (Beutel, 2009; Brown, 1962; Burnett, 2007; Conover, 1961; Crawford, 1985; CRMC, 1999; DeAngelis et al., 2008; Ernst et al., 1999; Lee, 1980; Lee and Olsen, 1985; Lee et al., 1997; Masterson et al., 2006; Nixon and Buckley, 2007; Satchwill and Gray, 1990,1991; Satchwill and Sisson, 1990; Thorne-Miller and Harlin, 1984; Thorne-Miller et al., 1983; Wright et al., 1949). These ecosystems are brackish with varying salinity (4–31 ppt) and flushing rates (Hougham and Moran, 2007; Meng et al., 2004; Olsen and Lee, 1982; Thorne-Miller et al., 1983). Nutrient cycles in these lagoons are driven by flushing of non-performing septic systems. Five of these lagoons have stabilized breachways and thus high flushing rates (residence time < 5 days) and salinity (27–31 ppt) (Point Judith, Winnipaug, Quonochontaug, Potters, Ninigret). They range in size from 1.5 to 7.8 km^2. The other