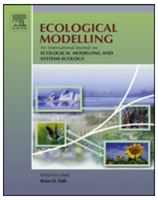
Ecological Modelling 222 (2011) 1743–1755

Contents lists available at ScienceDirect

Ecological Modelling

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



Calculating ecological carrying capacity of shellfish aquaculture using mass-balance modeling: Narragansett Bay, Rhode Island

Carrie Byron[a,b,*], Jason Link[c], Barry Costa-Pierce[a,d], David Bengtson[a]

[a] University of Rhode Island, Department of Fisheries, Animal and Veterinary Sciences, Kingston, RI 02881, USA
[b] Gulf of Maine Research Institute. 350 Commercial Avenue, Portland, ME 04101, USA
[c] National Marine Fisheries Service, Northeast Fisheries Science Center, 166 Water Street, Woods Hole, MA 02543, USA
[d] Rhode Island Sea Grant College Program, University of Rhode Island, Narragansett, RI 02882, USA

ARTICLE INFO

Article history:
Received 3 September 2010
Received in revised form 3 February 2011
Accepted 8 March 2011
Available online 31 March 2011

Keywords:
Carrying capacity
Aquaculture
Shellfish
Modeling
Ecopath
Narragansett Bay

ABSTRACT

Increasing growth in the aquaculture industry demands ecosystem-based techniques for management if that growth is to be ecologically sustainable and promote equity among users of the ecosystems in which it occurs. Models of carrying capacity can be used to responsibly limit the growth of aquaculture in increasingly crowded coastal areas. Narragansett Bay, Rhode Island, USA is one such crowded coastal region experiencing a rapid increase in bivalve aquaculture. An ecosystem mass-balance model was used to calculate the ecological carrying capacity of bivalve aquaculture. Cultured oyster biomass is currently at 0.47 t km^{-2} and could be increased 625 times without exceeding the ecological carrying capacity of 297 t km^{-2}. This translates to approximately 38,950 t of harvested cultured oysters annually which is 4 times the total estimated annual harvest of finfish. This potential for growth is due to the high primary productivity and large energy throughput to detritus of this ecosystem. Shellfish aquaculture has potential for continued growth and is unlikely to become food limited due, in part, to the large detritus pool.

1. Introduction

Growth of bivalve aquaculture worldwide (Costa-Pierce, 2008a; FAO, 2009) presents new challenges in coastal management. This growth is happening in both developing and industrial countries in nearshore coastal environments where user conflict is high (Costa-Pierce, 2008a; Hamouda et al., 2004). Over 50% of the human population lives within 100 km of the coast and several industries compete for use of coastal resources (Martínez et al., 2007).

One such bay with increasing aquaculture and high user conflict is Narragansett Bay, Rhode Island (RI), USA. Approximately half of Rhode Island's aquaculture takes place in Narragansett Bay. In the matter of 6 years (2001–2007), the industry grew exponentially from a $300,000 to a $1,600,000 industry doubling the number of farms and submerged land under lease (Alves, 2007). Ninety-nine percent of the aquaculture in Rhode Island is oysters (*Crassostreavirginica*). On a global scale, this industry is quite small. However, given that Rhode Island (RI) is the smallest and second most densely populated state in the United States, the rate of growth is notable.

Over the past decade, bivalve aquaculture has progressed in technological, political, and social sustainability (Costa-Pierce, 2008a,b; National Research Council, 2010). Rearing and harvesting techniques are more efficient (Costa-Pierce, 2008a,b). Technologies and policies aimed to mitigate the spread of disease have increased (Bushek et al., 2004; Forrest et al., 2009; Sapkota et al., 2008; Sindermann, 1984). Society's acceptance of bivalve aquaculture continues to grow in part due to educational campaigns aimed at increasing awareness to the ecosystem services provided by shellfish (Coen et al., 2007). Additionally, bivalve aquaculture is one of the most ecologically sustainable types of aquaculture (Shumway et al., 2003). Bivalve aquaculture has little negative impact on the benthos (Crawford et al., 2003; Forrest et al., 2009; Grant et al., 1995). Bivalves act as a benthic-pelagic link making planktonic nutrients available for benthic deposit feeders and submerged aquatic vegetation (Newell, 2004; Peterson and Heck, 1999, 2001) and improve water quality (Newell et al., 2002). Cages and other gear provide structure and habitat for a suite of other organisms thereby increasing biodiversity (Dealteris et al., 2004; Tallman and Forrester, 2007).

As social acceptance of bivalve aquaculture continues to increase, management strategies that promote sustainable industries become critical. The most important question managers need to ask is; "How much aquaculture can the system support?" This question can be addressed by calculating the carrying capacity of the system for bivalve aquaculture. Limiting aquaculture within the

---

* Corresponding author at: University of Rhode Island, Department of Fisheries, Animal and Veterinary Sciences, Kingston, RI 02881, USA. Tel.: +1 401 874 2668; fax: +1 401 874 7575.

E-mail addresses: carriebyron@my.uri.edu, cbyron@gmri.org (C. Byron), jason.link@noaa.gov (J. Link), bcp@gso.uri.edu (B. Costa-Pierce), bengtson@uri.edu (D. Bengtson).

0304-3800/$ – see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.ecolmodel.2011.03.010

carrying capacity is the most straightforward and obvious way to continued sustainability.

If we fail to manage within carrying capacity guidelines, there is potential to cause degradation of the system function. Tracadie Bay, PEI, is operating above its carrying capacity (Waite et al., 2005). Although a further increase in bivalve production may be possible, it would stress the system outside its normal range of variation (Filgueira and Grant, 2009). Similarly, river basins (rias) of the Galician area in northern Spain are operating at carrying capacity with no room for growth of the industry (Duarte et al., 2008; Smaal, 2002). Systems such as these threaten the ecosystem sustainability for, not only their own, but other industries as well. Social equity is likely to decline as user-conflict increases with environmental degradation.

1.1. *Carrying capacity*

The definition of carrying capacity has been extended to four types of carrying capacity that can be applied directly to 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. This information can be used to determine ecological carrying capacity using mass-balance modeling (Jiang and Gibbs, 2005; Mckindsey et al., 2006). Stakeholders in RI wanted to calculate ecological carrying capacity for current conditions in Narragansett Bay and were therefore, unwilling to accept any change in ecosystem function, biomasses, or energy flows.

1.2. *Modeling*

Ecopath is 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 other modeling approaches because it encompasses the full trophic spectrum, which is what makes it truly an ecosystem model appropriate for determining ecological carrying capacity. Most other shellfish carrying capacity models are at the production or farm scale (Bacher et al., 1998; Carver and Mallet, 1990; Nunes et al., 2003; Raillard and Ménesguen, 1994) which fails to incorporate all trophic levels equal to and higher than the bivalves. This approach is useful on a farm scale but is shortsighted for ecosystem management where several user groups depend on the stability and sustainability of other trophic levels across the entire ecosystem. Furthermore, Ecopath provides a methodology to standardize model outputs thereby making it easy to compare across systems.

Since Ecopath is a foodweb-based model, special emphasis is placed on predator–prey interactions and they are handled as they would be in a foraging arena (Walters et al., 1997). Overall, Ecopath is a good balance between simplicity and the complexity of other ecosystem models. Some applications of shellfish carrying capacity models only consider nutrients, plankton, detritus, and bivalves (Bacher et al., 1998; Hawkins, 2007; Raillard and Ménesguen, 1994; Smaal et al., 1998) which limit the scope of the model. Ecosystem models are more appropriate in scope, but can have unrealistic data demands and require advanced computer programming skills to operate (Plagányi, 2007). Ecopath provides a structured, yet flexible, framework for ecosystem modeling.

Ecopath, like any model, has shortfalls and limitations (Plagányi and Butterworth, 2004). Most shortcomings are attributed to user error such as uncritical use of Ecopath default settings. It is up to the modeler to change default settings so that they are appropriate for each functional group. Failure to do so treats all groups equally which can lead to erroneous conclusions (Plagányi, 2007). Perhaps the most unavoidable shortfall of any ecosystem model is the quantity and quality of data available to feed the model. We attempted to minimize this shortfall by using data collected at the model location to calculate input parameters and by employing a series of diagnostic tests to evaluate data parameterization and identify areas of data weakness that may need further investigation prior to model balancing (Link, 2010).

An ecosystem model of Narragansett Bay, consisting of 14 functional groups, has been previously defined by Monaco and Ulanowicz (1997). It was originally designed and used to compare trophic structure and sustainability of three major Atlantic bays; Narragansett Bay, Chesapeake Bay, Delaware Bay. These original models included no fisheries or aquaculture. Including both activities in the model are essential to fully understand the dynamics and function of the system. In order to aid the development of a long-term plan for aquaculture in Rhode Island, a working group of the state aquaculture regulatory agency recommended that the ecological carrying capacity of Narragansett Bay (and other coastal waters) for oyster aquaculture be determined. The purpose of this study was to update the Ecopath model of Narragansett Bay developed by Monaco and Ulanowicz (1997) and to use the updated model to calculate that ecological carrying capacity by increasing farmed oyster biomass until the model became unbalanced. A similar modeling effort was conducted for Rhode Island’s coastal lagoons (Byron et al., 2011a). A noteworthy aspect of these efforts is the inclusion of a wide variety of stakeholders in the development and application of the models (Byron et al., 2011b).

2. Methods

2.1. *Study area*

Narragansett Bay (355 km^2) in Rhode Island, USA (W71°20$'$ N40°35) is an eutrophic, well-mixed estuary with relatively little fresh water input (Saarman et al., 2008), residence time of 26 days, an average depth of 9 meters (Boothroyd and August, 2008; Nowicki and Nixon, 1985a,b) and average yearly temperature of 11.24 °C (Oviatt et al., 2002; Pilson, 2008; http://www.narrbay.org/physical_data.htm). Narragansett Bay has been well studied and modeled over the past 3 decades (Desbonnet and Costa-Pierce, 2008; Kremer and Nixon, 1978; Monaco and