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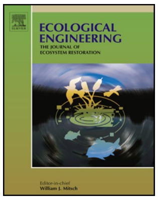

Emergy analysis to evaluate the sustainability of two oyster aquaculture systems in the Chesapeake Bay

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ABSTRACT

Oyster aquaculture is a growing industry in Maryland, USA and other coastal regions with significant estuaries that naturally provide the necessary salinity, food resources, and water flow for oyster growth. Although scientists, industry, and policy-makers promote oyster aquaculture as a sustainable business, studies to determine the environmental sustainability of oyster farming have focused on local environmental impacts without an analysis of the resources required and the overall ecological support needed to maintain a productive oyster farm. Since oyster aquaculture is a coupling of the human economy and the estuarine environment, understanding the sustainability of oyster aquaculture requires quantifying both the efforts of humans and the work of nature required to operate the farms. Emergy analysis, a quantitative tool for evaluating the energy and resources needed to support a process or product, converts the work of nature and human effort into a single metric, the solar emjoule (sej) for ease of comparison. The conversion allows the direct comparison of system flows of differing inputs, outputs and environmental impacts. This study compares two oyster (*Crassostrea virginica*) aquaculture farms in the Chesapeake Bay (Maryland, USA) that use differing methods of cultivation – floating rafts and on-bottom cages – through an emergy analysis. Our results showed that both farms are intensive systems driven primarily by imported emergy from the economy such as human labor, hatchery products, fuels, goods, and services. In comparison with other aquaculture products, cage- and raft-grown oyster production is supported by a higher percent of local renewable emergy (23% and 28%, respectively), in the form of particulate organic matter and estuarine water circulation. Our results showed a lower environmental loading ratio (3.2 and 2.5, respectively) than other forms of aquaculture; however the emergy yield ratio (1.3 and 1.4) was comparable to other aquaculture products. Between the two methods of rearing oysters, floating cage aquaculture had a lower environmental impact and a higher percentage of renewable emergy due to closer proximity to shore, which reduced motor fuel use, labor, and services. However floating cage used more emergy from hatchery products, due to the purchase of larger spat. Overall, we determined that oyster aquaculture has a lower global environmental impact, higher sustainability rating, and a higher net benefit to society than other forms of aquaculture. Reducing fuel use by locating aquaculture zone close to shore in floating cages and reducing electricity use by accessing natural water flows to drive upweller systems during the nursery stage are two opportunities to enhance sustainability of oyster aquaculture systems.

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1. Introduction

Over-harvesting, habitat destruction and diseases have decimated the once-abundant population of native Eastern oysters, *Crassostrea virginica*, in the Chesapeake Bay. Current oyster biomass estimates in the Chesapeake Bay are thought to be <1% of the historical abundance in the early 1800s and only 30% of suitable habitat remains (Newell, 1988; Rothschild et al., 1994; Wilberg et al., 2011). The risk of extirpation is so high that scientists have recommended a moratorium on harvesting wild oysters and have promoted oyster aquaculture to alleviate stress on wild populations while

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maintaining a commercially important fishery (Mann and Powell, 2007; Wilberg et al., 2011).

The environmental impact of oyster aquaculture systems is presently unclear. In the United States, disputes have arisen over aquaculture and the appropriate use of estuaries that have led to lawsuits in California (Drakes Bay Oyster Company V. Jewell, 2013) and Maine (Bernstein, 2007). In these cases, critics argue that aquaculture operations disrupt recreational and commercial activities in the local estuary, while proponents point to the economic and ecological benefits of oyster aquaculture to promote large-scale oyster aquaculture operations in estuaries.

Higgins et al. (2011) assessed the potential of oyster aquaculture to remove nutrients (C, N, P) from the estuarine environment through the process of bioassimiliation. They found that nitrogen removal is highly correlated to harvested shell length ($r^2 = 0.76$) and that an annual harvest of one million market-sized oysters (76 mm in shell length) would remove 132 kg TN/yr, 19 kg TP/yr, and 3823 kg TC/yr. Considering the rate of nutrient loadings into the Bay (8.4×10^7 kg-TN/yr; 4.03×10^6 kg-TP/yr; United States Geological Survey Department of Interior, 2000), the removal of nutrients through bioassimilation cannot be relied upon alone to manage the negative effects of eutrophication. To improve water quality in the Bay, Oyster aquaculture must be used in concert with land-based nutrient management programs (Rose et al., 2014).

Another possible benefit from aquaculture is the provision of refugia in the form of oyster cages and other submerged aquaculture gear. Researchers have found a greater abundance of commercially important finfish in and around oyster aquaculture gear than areas with muddy bottom that lack aqaculture (Tallman and Forrester, 2007; Erband and Ozbay, 2008; Marenghi and Ozbay, 2010). On the other hand, some consider that oyster aquaculture operations compete for space with submerged aquatic vegetation (SAV) zones that also provides critically important habitat for fish, but research has not been conclusive in this area (Vaudrey et al., 2009; Forrest et al., 2009).

Beyond local ecological impact assessments (Danovaro et al., 2004; Crawford et al., 2003; Mallet et al., 2006), one study quantified the carbon footprint of oyster aquaculture (Scottish Fisheries Research Forum, 2012) to find that oysters cultivated in the UK produced 1281 kg CO_2-eq per MT of oysters produced at farm gate. More than half of the CO_2 was emitted during the management of the grow-out period, when oyster bags were constantly cleared of fouling organisms, sorted and re-bagged by size to allow for faster growth. This study provided an indication of the intensity of oyster aquaculture operations but only on a single parameter (CO_2 emissions). Shumway et al. (2003) added qualitative information concerning the sustainability of oyster farming by focusing on other parameters such as nutrient pollution reduction and establishment of artificial reef habitat.

Significant questions remain including identification of the environmental impact of oyster aquaculture on a global scale and the level of resource consumption during the production of oysters for the half-shell market, which are fundamental to sustainability. Emergy analysis is a systematic approach established by Odum (1988, 1996) who defined emergy as “the available energy of one kind previously used up directly or indirectly that was used to produce a service or product.” It is an approach that integrates all upstream processes required to make necessary resources available and quantifies all inputs – from the environment and from the human economy – to a system or process on the same unit of measure; joules of solar energy, i.e. the solar emjoule (sej).

Doing so allows comparisons of different qualities of energy and materials with the same unit of measure and provides an understanding of the relationship between the environment and industries that other analysis methods do not currently provide (Ingwersen, 2011; Neri et al., 2013). This approach was chosen for an analysis of oyster aquaculture because cultivation of oysters is driven by biotic and abiotic factors. Emergy analysis offers insights about the links between the estuarine environment and the oyster industry. Environmental sustainability can then be evaluated quantitatively by comparing emergy inputs from the human economy to the renewable emergy supplied by the environment. Presumably, systems that utilize more renewable emergy have a lower environmental impact and are considered more sustainable because a greater proportion of their basis is replenished as fast as it is used. Ulgiati and Brown (1998) define sustainability by two essential aspects of systems. They argue that the sustainability of a system is related to its environmental impact and its yield. A sustainable system must be environmentally sound so that it does not degrade the natural systems that support it, and every system must provide a yield to society, lest it be outcompeted by systems that provide a greater yield. Moreover, if a system cannot yield an emergy benefit to the system that contains it, then the larger system becomes less productive and less able to sustain its internal sub-systems. In short, systems that do not contribute to the functioning of society or biosphere ultimately degrade their own ability to last. In order to determine whether this is the case, one must obtain an objective measure of sustainability that incorporates both determining factors—impact and net emergy yield.

When analyzing a product or service, the fundamental assumption of emergy analysis is that the contribution of a resource to a system is proportional to its emergy—the amount of work required to produce it (Brown and Herendeen, 1996). The work required is reflected in a resource’s solar transformity, which is the amount of solar emjoules required to produce or maintain a single joule of a specific kind of energy or a gram of a specific kind of material. Transformities are expressed as solar emjoules per joule or gram (sej/J; sej/g). The more energy transformations required to produce a product or service, the higher its transformity (Odum, 1996). The transformity is multiplied by the amount of a resource to obtain a measure of its emergy input (sej). The resultant emergy input of a resource is then proportional to its contribution to the process and provides a measure of ecological support needed for the system.

1.1. Oyster aquaculture in Maryland

Cultivation of the native Eastern oyster (*C. virginica*) has only recently been developed in Maryland along the Chesapeake Bay. Changes in fisheries management policy have made bottom leases more accessible to aquaculturalists (Maryland Department of Legislative Services, 2013a) and the development of large-scale hatcheries in the region have made triploid stock more accessible, both for restoration efforts and aquaculture. Private oyster aquaculture businesses had leased 175 acres of Bay water column area for rearing oysters by 2013, and 115 acres were under review for future leases at the end of 2013 (Maryland Department of Natural Resources, 2013b).

A significant development in the Chesapeake Bay has been the success of the Horn Point Hatchery at the University of Maryland’s Center for Environmental Science on the Eastern Shore and the hatchery at the Virginia Institute of Marine Science in Norfolk, Virginia. These hatcheries now produce selected genetic stocks of disease resistant, triploid oysters that are available for aquaculturalists to purchase at the eyed-larvae stage, cultched spat or attached to shell (spat-on-shell) for cultivation in open-systems.

The choice of larvae over cultched spat matters because eyed-larvae must first be allowed set to shell and grow to certain length before they can be deployed in the open estuary. First, the animals are set to small bits of shell in an on-shore aquaculture system. This process is referred to as “remote setting.” Once they have set to shell, the oysters are then placed in protected nursery systems before they are deployed in cage or rafts in the estuary.

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