Emergy Analysis for Quantifying Nutrient Regulating Ecosystem Services of a Subtidal Oyster Reef

Brittany N. Blomberg, Paul Montagna, Jennifer Beseres Pollack, David Yoskowitz

ABSTRACT

Oyster reefs are an important component of estuarine ecosystems and provide many ecological and economic benefits. Though traditionally prized as an important food source, oysters have gained greater recognition for providing numerous other ecosystem services (e.g., cultural and regulating services). Regulating services provided by oyster reefs include disturbance regulation (e.g., buffer storm surge and protect shorelines), sediment retention (e.g., stabilize sediment and control erosion) and nutrient regulation (e.g., reduce water column nutrients). Oyster reefs play a major role in the acquisition, processing and storage of nutrients within estuaries, and help maintain ecologically-acceptable levels of major nutrients, such as nitrogen. This research focuses on nutrient regulation services provided by a subtidal oyster reef in Texas and their value as quantified through energetic modeling and emergy analysis. In this study, the service of nutrient regulation is valued as the amount of nutrients (i.e., nitrogen) removed from the system. As oysters filter water to feed, they excrete excess particles as biodeposits. Nitrogen shunted from the water column to sediments via oyster biodeposits and waste may then undergo burial or denitrification, resulting in nitrogen removal from the system. To adequately represent the importance of oyster reefs to society beyond typical market values, numerous ecosystem services important for human well-being must be included. By linking emergy analysis to ecosystem services, the total value of ecosystems can be quantified.

INTRODUCTION

Eastern oysters, *Crassostrea virginica*, are the most common oysters in North America, forming extensive reefs in estuaries throughout their range (Atlantic coast from Canada to Brazil) (Beck et al. 2009). As a foundational species, oysters contribute to the integrity and functionality of estuarine ecosystems, and are an important ecological and economic resource. Though traditionally prized as an important food source, oysters have gained greater recognition for providing numerous other ecosystem services. Ecosystem services are contributions from ecosystems that, directly or indirectly, “support, sustain, and enrich human life” (Yoskowitz et al. 2010). Such contributions include goods, services, and cultural benefits humans receive from ecosystems.

As filter feeders, oysters play a significant role in estuarine nutrient cycles and the regulation of nutrients and wastes (Dame et al. 1984, Beseres Pollack et al. 2013). Based on filtration rates estimated by Beseres Pollack et al. (2011), an individual oyster in Texas can filter over 7 gallons of water each day. As oysters filter bay waters, they remove excess nutrients, pollutants, heavy metals, sediments, bacteria, plankton, and may play an important role in decreasing the occurrence of harmful algal blooms (Beck et al. 2009). This filtering activity improves water quality and clarity, which can also enhance surrounding habitats.
Oyster populations have suffered severe losses during the past century. The majority of native oysters in North America and Europe are in poor condition (90-99% lost) or functionally extinct (> 99% lost) compared to historical population estimates (Beck et al. 2009). The Gulf of Mexico is the largest ecoregion where oyster reefs are considered in fair condition (50-89% lost); the region also supports the world’s largest natural oyster fishery (Beck et al. 2009).

In the last 20 years, restoration of oyster reef habitat has become a broader priority for restoring a variety of important ecosystem services. Several market and non-market methods have been used to quantify ecosystem services to determine the success of restoration projects (Pendleton 2010). Valuation of market goods provided by ecosystems is relatively simple: economic markets exist and humans pay a particular price for such goods. However, price is not equivalent to value, and ecosystems are severely undervalued when only market prices are considered. Methods for valuing ecosystem services in which a market does not exist are more difficult. Non-market valuation techniques rely on revealed or stated preferences. Revealed preference methods value ecosystem services based on real actions and choices people make. Stated preference methods are based on hypothetical values typically obtained from surveys (Pendleton 2010). To adequately represent the importance of oyster reefs to society beyond typical market values, we must include the numerous ecosystem services important for human well-being. Emergy accounting methods are desirable because they can quantify a variety of ecosystem services in common energy-based units (Odum and Odum 2000). By linking emergy analysis to ecosystem services, we can begin to quantify the total value of ecosystems.

The goals of the present study are: 1) to quantify nutrient regulating ecosystem services (i.e., nitrogen removal) provided by a natural oyster reef in South Texas using emergy accounting methods, and 2) assess the success of a nearby restored reef using the same methods.

**METHODS**

**Study Area**

Copano Bay is located within the Mission–Aransas Estuary on the mid Texas coast (Figure 1a). The area is characterized by a semi-arid, subtropical climate with infrequent rain events. On average, evaporation (151.3 cm yr⁻¹) exceeds precipitation (88.6 cm yr⁻¹) (Mooney 2009). Average freshwater inflow to the estuary is relatively low (10 m³ s⁻¹) (Montagna et al. 1996). Salinity generally ranges from 10 to 20 psu, though high salinity conditions (> 40 psu) can occur during periods of drought (Montagna et al. 1996, Beseres Pollack et al. 2011). The estuary is microtidal, experiencing an average tidal range of 0.15 m (Mooney 2009). Water movement is predominantly wind-influenced and the estuary remains well-mixed. Residence times average 360 days, but can be as long as 3 years (Beseres Pollack et al. 2011; Montagna et al. 1996).

Oyster reefs are a common feature throughout the estuary (Figure 1). Reefs are primarily subtidal, and are most prominent in areas of low to moderate salinity. This study focuses on Lap Reef, a natural oyster reef complex occupying approximately 387,000 m² in Copano Bay (Figure 1a). A restoration project completed in 2011 involved the construction of eight reef mounds in the Lap Reef complex, for a total of 4,800 m² new habitat (Figure 1b).

**Definition of System**

The modeled system is defined as the area of the Lap Reef complex. Boundaries are the extent of the reef, including the overlying water column (1 m) and the surface sediments (2 cm). Nutrient regulating ecosystem services are represented by the functional flows that result in the removal of bio-deposited nitrogen from the system, either through burial into deep sediments or denitrification and release to the atmosphere as nitrogen gas (N₂; Figure 2).
Figure 1. Location of the study area within the Mission-Aransas Estuary, Texas, USA; oyster reefs are indicated in dark grey. (a) The Lap Reef complex in Copano Bay is indicated by the dashed box; (b) Location of the restored reef within the Lap Reef complex.

Figure 2. Conceptual model of nutrient regulating ecosystem services (i.e., nitrogen removal) provided by an oyster reef. System boundaries include the extent of the reef, overlying water column (1 m) and surface sediments (2 cm). Nitrogen is removed either through denitrification by mineralizing bacteria and subsequent release of nitrogen gas (N₂) to the atmosphere or by burial into deep sediments.

Energetic Model and Emergy Analysis

A steady-state energy model of ecological flows associated with nitrogen removal from the reef system was developed (Figure 3). Flows of nitrogen were estimated from the literature and converted to energy units (Table 1). Solar energy was chosen to be the only energy source for this assessment because of the semi-arid climate, low freshwater inflow and microtidal conditions.
Table 1. Values for the forcing functions, system components or storages, and pathway flows in the Lap Reef ecosystem model (Figure 3). See Notes.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Value</th>
<th>Units</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forcing Functions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$J_1$</td>
<td>Incident solar radiation</td>
<td>6.04E+09</td>
<td>J m$^{-2}$ y$^{-1}$</td>
<td>1</td>
</tr>
<tr>
<td>$J_R$</td>
<td>Albedo</td>
<td>10</td>
<td>%</td>
<td>2</td>
</tr>
<tr>
<td>System Components or Storages</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$P$</td>
<td>Phytoplankton</td>
<td>0.06</td>
<td>g N m$^{-2}$</td>
<td>3</td>
</tr>
<tr>
<td>$F$</td>
<td>Filter feeders (i.e., oysters)</td>
<td>6.70</td>
<td>g N m$^{-2}$</td>
<td>4</td>
</tr>
<tr>
<td>$D$</td>
<td>Detritus</td>
<td>0.07</td>
<td>g N m$^{-2}$</td>
<td>5</td>
</tr>
<tr>
<td>Pathway Flows</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$J_1$</td>
<td>Solar energy available for photosynthesis</td>
<td>5.44E+09</td>
<td>J m$^{-2}$ y$^{-1}$</td>
<td>6</td>
</tr>
<tr>
<td>$J_2$</td>
<td>NPP for phytoplankton</td>
<td>4.16E+06</td>
<td>J m$^{-2}$ y$^{-1}$</td>
<td>7</td>
</tr>
<tr>
<td>$J_3$</td>
<td>Filtration of phytoplankton</td>
<td>1.39E+06</td>
<td>J m$^{-2}$ y$^{-1}$</td>
<td>8</td>
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<tr>
<td>$J_4$</td>
<td>Biodeposits</td>
<td>6.93E+05</td>
<td>J m$^{-2}$ y$^{-1}$</td>
<td>9</td>
</tr>
<tr>
<td>$J_5$</td>
<td>Detritus consumed by bacteria</td>
<td>5.55E+05</td>
<td>J m$^{-2}$ y$^{-1}$</td>
<td>10</td>
</tr>
<tr>
<td>$J_6$</td>
<td>Detritus available for burial</td>
<td>1.39E+05</td>
<td>J m$^{-2}$ y$^{-1}$</td>
<td>11</td>
</tr>
<tr>
<td>$J_7$</td>
<td>Denitrification</td>
<td>1.39E+05</td>
<td>J m$^{-2}$ y$^{-1}$</td>
<td>12</td>
</tr>
<tr>
<td>$J_8$</td>
<td>Burial</td>
<td>8.32E+04</td>
<td>J m$^{-2}$ y$^{-1}$</td>
<td>13</td>
</tr>
</tbody>
</table>

Energy flows were set up in matrix form showing relevant flows of energy to and from each model component (Figure 4a). The Microsoft Excel Solver tool was used to calculate transformities for each energy transformation process represented in the matrix. This method has been proven to be a valid way to estimate transformities (Bardi et al. 2005).

The calculated transformities were then applied to the energy flows of nitrogen removal to quantify the nutrient regulating ecosystem services in emergy terms according to:

\[
\text{Emergy (seJ)} = \text{Energy (J)} \times \text{Transformity (seJ/J)}
\] (1)

Transformities calculated for Lap Reef are applied to data from the restored reef to assess restoration success. Data collected during monitoring of the restored reef at 5, 10 and 13 months post-construction.
were used to obtain energy values for each component and flow in the same manner as for the natural reef. Additional emergy inputs of the restoration process are not included in the model at this time.

RESULTS AND DISCUSSION

An energy systems diagram (Figure 3) illustrates the ecological flows associated with nitrogen removal in the oyster reef system. Oysters transfer nitrogen from the water column to detritus via biodeposits at a rate of 6.93 E+05 J m⁻² y⁻¹ (Figure 3, transformation x4). Biodeposits are subject to consumption by bacteria or deposition to sediment (x5), from which denitrification and release of N₂ gas (x6) or burial into deep sediments (x7) can occur. Energy flows associated with nutrient regulating ecosystem services of denitrification and burial were determined to be 1.39 E+05 and 8.32 E+04 J m⁻² y⁻¹, respectively (Figure 3, Table 1).

Energy flows were set up in matrix form in Microsoft Excel (Figure 4a), and the Solver algorithm was used to calculate solar transformities for each transformation process. Unknown transformities were manipulated subject to the constraints set (e.g., emergy in = emergy out). The solution is shown in Figure 4b (precision = 0.01; iterations = 100,000). Transformities for the ecosystem service flows were determined to be 4.35 E+10 and 1.81 E+10 seJ/J for denitrification (x6) and burial (x7), respectively. Annual emergy values of the ecosystem service flows of nitrogen removal were determined according to Equation 1 for each process as follows:

\[
\text{Denitrification: } (1.39 \times 10^5 \text{ J m}^{-2} \text{ y}^{-1}) \times (4.35 \times 10^{10} \text{ seJ/J}) = 6.03 \times 10^3 \text{ seJ m}^{-2} \text{ y}^{-1} \quad (2)
\]

\[
\text{Burial: } (8.32 \times 10^4 \text{ J m}^{-2} \text{ y}^{-1}) \times (1.81 \times 10^{10} \text{ seJ/J}) = 1.51 \times 10^3 \text{ seJ m}^{-2} \text{ y}^{-1} \quad (3)
\]

Thus, the emergy value of nutrient regulating ecosystem services performed by oysters at Lap Reef is 7.5 E+15 seJ m⁻² y⁻¹. Denitrification and burial of nitrogen were estimated for the restored reef at 5, 10, and 13 months post-construction according to the same energy systems model used for Lap Reef. Transformities obtained for Lap Reef were used to calculate emergy values of the ecosystem service flows from the restored reef during each time period examined according to Equation 1.

![Figure 4](image-url)

**Figure 4.** Calculation of transformities in Microsoft Excel using the Solver method. (a) Matrix set up (flows in J m⁻² y⁻¹); (b) Resulting solar transformities (seJ/J).
Figure 5. Emergy values (seJ m$^{-2}$ month$^{-1}$) of nutrient regulating ecosystem services provided by the natural reef (before restoration) and restored reef (5, 10 and 13 months post-construction).

Table 2. Enhancement (%) of reef area (m$^2$) and provision of nutrient regulating ecosystem services (seJ month$^{-1}$) via restoration at Lap Reef.

<table>
<thead>
<tr>
<th>Reef area (m$^2$)</th>
<th>Natural Reef</th>
<th>Restored Reef</th>
<th>Combined</th>
<th>Enhancement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nutrient regulating ecosystem services provided (seJ month$^{-1}$)</td>
<td>387,000</td>
<td>4,800</td>
<td>391,800</td>
<td>1.2%</td>
</tr>
<tr>
<td>5 mo.</td>
<td>2.37E+20</td>
<td>1.58E+17</td>
<td>2.37E+20</td>
<td>0.1%</td>
</tr>
<tr>
<td>10 mo.</td>
<td>2.37E+20</td>
<td>8.19E+18</td>
<td>2.45E+20</td>
<td>3.5%</td>
</tr>
<tr>
<td>13 mo.</td>
<td>2.37E+20</td>
<td>5.72E+18</td>
<td>2.43E+20</td>
<td>2.4%</td>
</tr>
</tbody>
</table>

Emergy flows of denitrification and nitrogen burial from the natural reef were compared to changes in the restored reef over time (Figure 5). Five months post-construction, the restored reef had approximately 50% spat and 25% sub-adult oyster abundances compared to the natural reef and provided minor ecosystem service value (3.3 E+13 seJ m$^{-2}$ month$^{-1}$). After ten months, the restored reef had nearly 30% more oysters than the natural reef, and was providing nearly three times the emergy value of nitrogen removal per unit area (1.7 E+15 seJ m$^{-2}$ month$^{-1}$). Between 10 and 13 months post-construction, there was evidence of an oyster die-off caused by the parasite Perkinsus marinus. Despite causing a decrease in the emergy value of nitrogen removal, the restored reef still provided nearly twice the ecosystem service value as the natural baseline (1.2 E+15 seJ m$^{-2}$ month$^{-1}$).

Emergy analysis results indicate that the restoration of oyster reef habitat has increased the value of nutrient regulating ecosystem services (i.e., nitrogen removal through denitrification and burial of oyster biodeposits) in greater proportion than the increase in total reef area. The restoration project created 4,800 m$^2$ of new oyster habitat, representing a 1.2% increase of reef area to the Lap Reef complex. Enhancement of ecosystem service provisioning via restoration to the Lap Reef complex was calculated for 5, 10 and 13 months post-construction (Table 2). After 10 months, the restored reef enhanced the
provisioning of nutrient regulating ecosystem services by 3.5%, compared to the 1.2% increase in reef area. Thus, this assessment indicates that the restored reef is providing a greater service per unit area. These results support the notion that restoration success should be quantified in functional terms (e.g., services provided), as opposed to more common structural terms (e.g., area restored).

CONCLUSIONS

Further work could be conducted to develop more comprehensive models. In particular, additional energy inputs should be examined. The conditions of the area indicate that wind may be the most important forcing function, because the climate is dry with low freshwater inflow and microtidal conditions. The area experiences relatively high wind conditions, and estuarine circulation is predominately wind-driven. Additionally, a more complete energy analysis of the restored reef should include the initial energy inputs of construction. However, model complexity doesn’t always increase accuracy of predictions (Turner et al. 2014), and the analyses presented here are likely sufficient for quantifying ecosystem service value and assessing restoration success in terms of nutrient regulating ecosystem services (i.e., nitrogen removal).

With continued degradation of ecosystems and increasing restoration efforts, better metrics of ecosystem value and restoration success are needed. The most common metric of restoration success is area restored. This research evaluates the impact of restoration on ecosystem services by using emergy accounting methods. It shows that ecosystem services do not necessarily follow a linear relationship with area of habitat restored. It also illustrates the importance of examining ecosystem service changes during development of restored habitats. As restoration and conservation become broader priorities for restoring and conserving the provisioning of ecosystem services, it is important to quantitatively value ecosystems and the array of services they provide on a common basis, independent of market value.

ACKNOWLEDGMENT

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REFERENCES


NOTES
The following factors were used to convert from nitrogen to carbon (x 6.625), and from carbon to energy (x 10 kcal/g carbon and x 4186 J/kcal).

1. Incident solar radiation = 4.6 kWh/m$^2$/day (US Department of Energy 1999; 30 year annual average 1961-1990, measured at Corpus Christi, TX) = (4.6 kWh/m$^2$/day)(3.6E+06 J/kWh) = 1.66E+07 J/m$^2$/day

2. Albedo: assume 10% of solar radiation

3. Phytoplankton (Pollack et al. 2013) = (4.2 μg Chl-a/L)(14 μg N/μg Chl-a)(1000 L/m$^3$)(0.000001 g/μg)(1 m) = 0.0588 g N/m$^2$

4. Oysters (Pollack et al. 2013) = (0.938 g dry tissue/individual)(102 individuals/m$^2$)(0.07 g N/g dry oyster tissue) = 6.7 g N/m$^2$

5. Total detritus = water column (1 m) + sediment (2 cm)
   Water column detritus (TSS) = 30.6 mg TSS/L (Pollack et al. 2013)*0.001 g/mg*2.1 mg N/g TSS (Newell et al. 2005) = 0.06426 mg N/L = 0.000001 g N/m$^2$
   Sediment detritus = 3.6 g dry sediment/m$^2$/2 cm (Montagna 2007)* 0.00152 g N/g dry sediment (Montagna 1997) = 0.0055 g N/m$^2$/2 cm
   Total detritus = (0.06426 g N/m$^2$) + (0.0055 g N/m$^2$) = 0.07 g N/m$^2$

6. Solar energy absorbed = (1.66E+07 J/m$^2$/day)(1-0.10) = 1.49E+07 J/m$^2$/day

7. Phytoplankton net primary production (NPP) = gross primary production (GPP) – respiration (R); assume R = 15% of GPP; C:N ratio for phytoplankton = 6.7 (Kemp et al. 1997)
   NPP = 1.03 mg O$_2$/L/day (Russell and Montagna 2007)*0.85*0.313 mg C/mg O$_2$ (Plutchak et al. 2010) = (0.274 g C/m$^2$/day)/6.7 = 0.041 g N/m$^2$/day

8. Oyster grazing on phytoplankton = clearance rate (CR, μg N/individual/min) = filtration rate (FR, ml/individual/min)*food (μg N/L)*(0.001 L/ml); food = 0.085*Chl-a (Pollack et al. 2013)
   CR = 18.35 ml/individual/min (Pollack et al. 2010)*[(0.085)(4.2 μg Chl-a/L)(14 μg N/μg Chl-a)]*(0.001 L/ml) = (0.092 μg N/individual/min)(1440 min/d)(0.000001 g/μg)(102 individuals/m$^2$) = 0.0135 g N/m$^2$/day

9. Oyster biodeposits: assume 50% N ingested is transferred to detritus as biodeposits (Pollack et al. 2013) = (0.5)(0.013 g N/m$^2$/day) = 0.0067 g N/m$^2$/day

10. Detritus consumed by bacteria: assume bacteria consume 80% of all detritus deposited = (0.8)(0.0067 g N/m$^2$/day) = 0.0054 g N/m$^2$/day

11. Detritus available for burial: assume remainder (20%) of detritus not consumed by bacteria accumulates in sediment and is subject to burial processes = (0.2)(0.0067 g N/m$^2$/day) = 0.0013 g N/m$^2$/day

12. Denitrification: assume 20% denitrification rate of biodeposited-N (Pollack et al. 2013) = (0.2)(0.0067 g N/m$^2$/day) = 0.0013 g N/m$^2$/day

13. Detritus buried: assume 10% burial rate of biodeposited-N (Pollack et al. 2013) = (0.1)(0.0067 g N/m$^2$/day) = 0.0007 g N/m$^2$/day