Production of enough live bait to be profitable requires intensive production methods and technology. Considerable knowledge and training in aquaculture and water quality is needed to manage this business. The quarry owner and the business partner did not have any training or experience in aquatic biology, aquatic science or aquaculture. Furthermore, the partner wanted to retire to manage the live bait venture.

Potential use of the quarry for aquaculture poses challenges. Nutrients in effluents associated with intensive feeding could stimulate moderate to dense algal blooms in the quarry. Loss of water clarity could affect much of the marine life presently found in the quarry ecosystem. Additionally there are potential environmental protection issues associated with waste effluents. Some type of low management intensity, low-maintenance aquaculture would have better chances of success.

Limestone rock formations typically have many cracks and fissures. Water seeps into and percolates through the limestone and can eventually create larger channels. Mammoth Cave in Kentucky, USA was formed this way. Abandoned limestone quarries often fill with fresh water and the water is clear enough in some of these for SCUBA diving (Fig. 1).

Over the years, limestone has been mined in the Florida Keys for road construction. Some abandoned quarries in the area have filled with seawater through cracks, fissures and channels in the limestone formations. In July 2015, two individuals in Florida were seeking aquaculture information about producing live bait for the Florida Keys sport fishing industry. One owns an abandoned limestone quarry in the Florida Keys near Looe Key Reef that is filled with seawater. The quarry surface area is 4.9 ha and the average depth about 9 m.

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Growing live rock and coral for retail and wholesale markets represents a good low-management, low-technology aquaculture business option for a marine quarry. Small-scale ornamental marine fish production could integrate well with live-rock aquaculture. The potential impact of live rock culture on the pre-existing quarry environment and ecosystem could be minimal to non-existent.

**Live Reef Requirements**

Publicly available information about commercial production of live rock, especially environmental requirements, is sparse. Many if not most of the organisms that colonize live rock inhabit coral reefs. Wheaton et al. (1996) listed 22 animal phyla can be found on coral reefs. It is likely that the physical requirements (Table 1) of living coral reefs would be suitable and desirable for live rock aquaculture. The potential impact of live rock culture on the pre-existing quarry environment and ecosystem could be minimal to non-existent.

**Rationale for Live Rock/Artificial Reef Culture**

An article on live rock aquaculture was published in *World Aquaculture* in 2003 (Falls et al. 2003a). Pieces of limestone or artificial substrate were placed on the ocean floor in Florida coastal waters and native marine organisms colonized the substrate. Many species can be found on live rock including corals, coralline (calcareous) algae, anemones, octocorals, brittle stars, sea urchins and mollusks (Falls et al. 2003b). Cultivation of these rocks and creatures has become its own specialized tropical marine aquarium industry.

**TABLE 1. Physical requirements of coral reefs (adapted from Wheaton et al. 1996).**

<table>
<thead>
<tr>
<th>FACTOR</th>
<th>REQUIREMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>High light</td>
<td>Surface irradiance of 2,000 µE/m² sec</td>
</tr>
<tr>
<td>High oxygen concentration</td>
<td>5-7 mg/L</td>
</tr>
<tr>
<td>Low turbidity</td>
<td>0.01-0.10 mg/L</td>
</tr>
<tr>
<td>Low nutrient concentration</td>
<td>0.10-1.0 µM (N or P)</td>
</tr>
<tr>
<td>Stable temperature</td>
<td>23-30 C</td>
</tr>
<tr>
<td>Stable salinity</td>
<td>33-36 ppt</td>
</tr>
</tbody>
</table>

(Continued on page 62)
help recycle nutrients in oligotrophic tropical waters where reefs typically are found. Zooxanthellae need light for photosynthesis and survival. Water clarity, which affects light penetration and intensity, is critical for corals as well as coralline algae. Therefore, a minimum water clarity (light intensity) is needed.

The amount of surface light reaching a given depth can be determined from the equation $I_z = I_0 e^{-kz}$, where $I_z$ is surface light intensity; $I_0$ is the light intensity at depth $z$ (in m); $e$ is the natural logarithm; and $k$ is the extinction coefficient. The extinction coefficient is related to light wavelength and the level of suspended particulate matter. In clear coastal waters, $k$ is about 0.15, while in turbid coastal waters it is around 0.46. In highly turbid waters of many harbors and estuaries, values of $k$ may be as high as 1.5 (Clark and Denton 1962). An extinction coefficient (or attenuation coefficient), $K_d$, can be estimated from Secchi disk depth measurements using the equation $K_d = 1.7/\text{Secchi disk depth}$ (in meters).

A live rock culture study was conducted by Hillsboro Community College at five locations in Florida coastal waters (Falls et al. 2003b). Using the light transmittance data reported for the five culture sites, calculated $K_d$ values ranged from 0.096 to 1.05. The overall average $K_d$ value was 0.36.

Looe Key Reef is located in the Looe Key National Marine Sanctuary (LKNMS) just off the coast of the Florida Keys. The reef and sanctuary are close to the latitude of the marine quarry under consideration. Most of LKNMS lies in shallow water 0-7 m deep (Lidz et al. 1985). Removing outliers from $K_d$ data collected at Looe Key Reef from 1995-2014 (Briceno 2015), the average ($n=56$) $K_d$ was 0.116 ± 0.053 (± SD).

Approximately 1.21 ha of quarry bottom lies within the 0-7 m depth range of Looe Key Reef. The reef $K_d$ value of 0.116 represents an approximate Secchi disk depth of 14.7 m. Local SCUBA divers report good visibility to an estimated depth of 10-12 m in the quarry. Quarry water appears to be sufficiently clear to allow adequate light penetration for live rock/coral survival and growth.

While light is critical for living reefs, water movement is equally important. Beyond wave action and strong currents created by storms, there is a continuous movement of water over coral reefs. Many of the organisms that colonize reefs are sessile. A constant flow of water is needed to distribute food and nutrients, enable oxygen and carbon dioxide exchange for respiration and photosynthesis, and facilitate reproduction and dispersal of larvae.

Ocean surface current speeds can be estimated as a percentage of the wind speed 10 m above the water. For wind speeds from 5 to 30 m/sec, total surface current speed would be 3.1 percent to 3.4 percent of wind speed (Weber 1983). Based on 36 years of data, the annual average prevailing wind speeds for Miami and Key West, Florida are 4.0 and 4.9 m/sec (NCDC 1998), respectively. Looe Key Reef is only a few miles from shore. It is reasonable to assume that the average prevailing wind speed at Looe Key Reef is within this range. Estimated total ocean surface current velocity for those wind speeds would be between 12.4 to 16.6 cm/sec.

Water current velocities were recorded at a Looe Key Reef moored monitoring station from 2005-2010 (Gramer 2015). The current had an average velocity of 20.5 ± 14.4 (± SD) cm/sec in water with an average depth of 23.1 ± 0.9 (± SD) m.

It is reasonable to assume that a live-rock reef in a quarry must have continuous water flow over its surface. A current of 12.4 to 20.5 cm/sec would be a reasonable target velocity for live rock and coral culture in a large closed system. Research in this area could be instructive. Solar-powered airlift technology using regenerative blowers represents a viable method for water circulation.

**Construction**

As with environmental requirements, there is limited information about commercial live rock culture sites regarding substrate size, type, shape, quantity, structure and its placement. The Hillsboro Community College live-rock research project placed substrate pieces of unspecified size in circular piles on the sea bottom in Florida coastal waters (Falls et al. 2003a, 2003b). These piles were 1.5-15.2 m in diameter and 0.9-1.5 m high. Substrate piles were placed at depths of 2-15 m. Various types of limestone and artificial substrate were used. Commercial live rock culture businesses have used 45.5 to 272.7 t of limestone/substrate to create individual reef sites in Florida’s public offshore waters (Falls et al. 2003a).

Circular piles would not be an efficient use of horizontal space. Long rectangular ridges, triangular in cross section, would provide more surface area for live rock growth. The size, spacing, lengthwise orientation (north-south vs. east-west), and triangular cross-section shape (Fig. 2) of ridges will affect the amount of substrate surface receiving light and the duration of light exposure.

Basically the quarry is a large closed system. A 4.86-ha surface area with an average depth 9.1 m would hold 444,200 m$^3$ of water. The estimated bottom area suitable for live rock/reef culture in the quarry is 1.2 ha. Assuming limestone density is 2,300 kg/m$^3$ and the open spaces within the ridges of limestone riprap account for 25 percent of ridge volume, it should be...
possible to place 5,178 t of limestone in rectangular ridges with triangular cross sections (1 m high with bases 2 m wide) in a culture area of 1.2 ha.

Harvests could begin 3 to 5 years after substrate placement (Falls et al. 2003a). Assuming a 10 percent annual harvest of live rock from the 5,178 t of limestone riprap placed, 518 t of live rock could be harvested and sold each year. Harvested rock would be replaced annually. If native marine ornamental fish are stocked as an added species to create a more diverse reef community, a sustainable percentage of those fish could also be harvested for sales. A sufficiently large number/biomass of live rock organisms and fish must remain to reproduce and maintain a harvestable population.

**Biomass**

The objective is to create a large self-sustaining ecosystem to culture the desired native species. Water clarity and quality must be maintained as closely as possible to that found in the seawater of a healthy live reef environment. Limestone rocks of suitable size and shape for the aquarium trade are placed over the culture area. Natural benthic organisms and other marine life are allowed to colonize these rocks over a several year period. Some seeding of native Florida marine life from cultured and/or other legal sources may be needed to improve the variety of species found on the live rock. Marine ornamental fish and other valuable seawater animals/plants could be stocked to enhance maintain a sustainable balance.

The biomass of organisms encrusting the substrate might not be determined by available surface area. In addition to light, zooxanthellae and other reef algae need phosphorus, nitrogen and other nutrients. The total biomass of organisms found on live rock will depend on quarry productivity – the natural aquatic food supported by quarry water – determined by nutrient availability. It is not known how much live rock/coral the quarry can support without adding nutrients.

The marine quarry has clear water, a good indicator that an aquatic environment has low nutrient concentration. Nutrient availability limits the amount of life the quarry can support. At low nutrient concentrations, biomass is determined by a self-sustaining (balanced) ecosystem. Carrying capacity will likely be controlled by nutrient availability and not oxygen demand. Too much nutrient input creates too much biomass. As the amount of available nutrient increases, the biomass increase is eventually limited by oxygen availability and respiration.

To increase the biomass of live rock organisms and harvest yields beyond carrying capacity, nutrients would have to be added to the system. This could conceivably be done with some form of integrated multi-trophic aquaculture, but this could be a delicate and difficult balancing act. Quarry water nutrients should not exceed those found in a healthy reef environment. Nutrient levels above natural concentrations could be detrimental to live rock and coral production by decreasing water clarity.

**Opportunity**

The quarry represents an opportunity for commercial aquaculture. Compared to open coastal waters, the quarry may provide a relatively stable environment that is potentially more sheltered from the impacts of storms. Marine limestone quarries can be used to create live reef/coral preserves. Placed substrate would be used to create artificial reefs for corals and other reef organisms that are or may become threatened or endangered. With the global decline of living coral reefs, the value of live rock aquaculture in quarries for preservation may be greater than that for profit.

**Notes**

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