# Advancement of Sunray Venus Clam *Macrocallista nimbosa* Aquaculture through Evaluation of Alternative Growout and Harvesting Methods

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## Introduction

*Development of Clam Culture in Florida*

The Florida shellfish aquaculture industry began in the mid-1980s along the east central coast. Declines in wild clam landings from the Indian River prompted clammers to investigate the potential of aquaculture as an alternative to fishing natural stocks. Due to a moratorium imposed on leasing by the Florida Department of Natural Resources (FDNR) in 1985, clam farms were located on existing shellfish cultch leases (originally used for extensive oyster cultivation) issued in perpetuity by the State of Florida under Chapter 370, Florida Statutes (F.S.). In 1989, 21 growers reported producing 5.9M clams at a farm gate value of $1M (FASS, 1990). To assist the emergent industry, a new lease program (10-year term and renewable) was authorized by the state legislature in 1988 under Chapter 253, F.S. and Chapter 18-21, Florida Administrative Code (F.A.C.), which provided for leasing of sovereign submerged lands for aquaculture (Andree, 1994). Special lease provisions were developed as part of the lease instrument, one of which was the prohibition of mechanical harvesting on the new leases. At the same time, researchers at Harbor Branch Oceanographic Institution, a marine research facility located on Florida's east coast, began evaluating culture technology developed in the Northeastern U.S. and adapting it to subtropical conditions (Vaughan *et al*., 1988). The result was the soft tray, now known as the bottom bag, which provides predator protection and serves as a harvesting device as it contains the clams. During the 1990s, federally funded programs trained hundreds of under-employed fishermen in shellfish cultivation and provided the infrastructure to establish over 1,100 acres of shellfish aquaculture leases on Florida's west coast (Colson and Sturmer, 2000). In 2007, 185M clams valued at $19M were produced by around 350 growers with an economic impact to the state estimated at $53M (Adams *et al*., 2009a).

*Potential of Sunray Venus Culture and Marketability*

The growth of the Florida shellfish aquaculture industry is a dramatic success story (Adams and Sturmer, 2004). However, the industry is built on a single clam species *Mercenaria mercenaria*. The sunray venus clam *Macrocallista nimbosa* is being explored as a potential aquaculture species to diversify the hard clam culture industry. The sunray venus is an attractive venerid clam, whose distribution ranges from the Carolinas to Florida and Gulf of Mexico states. During the 1960-70s, two million pounds of these clams were harvested in the Panhandle region of Florida. However, insufficient natural stocks, as well as the small size of the fishing grounds, limited the development of the fishery (Jolley, 1972). Growth experiments using marked individuals suggested that these clams could attain a length of three inches (40 g whole) within 12 months (Stokes *et al*., 1968), similar to growth rates of hard clams in Florida. The existence of a latent market and the potential growth

*Cooked, cultured sunray venus clams*
*Macrocallista nimbosa*

rate of the sunray venus clam, along with it being a native species, made it a logical choice as a candidate species for shellfish aquaculture.

Over a six-year period, research and extension faculty at the University of Florida (UF) and Harbor Branch Oceanographic Institute at Florida Atlantic University, along with industry partners, developed and tested technical methods to culture the sunray venus clams in Florida Sea Grant-funded projects. The project team used culture methods standard to those employed by the Florida hard clam culture industry as a starting point. Broodstock, collected from natural assemblages, were successfully collected and spawned, and larvae were reared to produce seed (Scarpa *et al*., 2008). The consumer acceptance of both cooked and raw sunray venus clams was evaluated in local markets, providing an assessment of consumers' opinion of the product with respect to a number of product attributes (Adams *et al*., 2009b). Cultured sunray venus clams were premiered at the 2011 International Boston Seafood Show, where over 250 buyers expressed a high degree of product acceptance.

Growout production was also examined and a strong relationship between soil type preference and this infaunal mollusc was documented (Ellis and Osborne, 2011). Field trials using the bottom bag method revealed variability in production characteristics; as such, this method may not be reliable for sunray venus culture (Sturmer *et al*., 2009). Bottom culture (planting under cover nets), a method used in other states for the culture of hard clams, may be more suitable. A small test plot of bottom-planted sunray venus clams resulted in faster growth and no shell deformities (a problem encountered in bottom bag culture). However, the State of Florida limits the use of mechanical harvesting on shellfish aquaculture leases through special lease provisions. Growers would be limited to manual methods, such as a hand rake, in harvesting sunray venus clams grown under bottom nets, which may not be commercially viable.

*Mechanical Harvesting of Shellfish*

Shellfish harvesting has evolved over time from manual collection to the use of mechanical devices. Molluscan shellfish were first harvested by treading or hand picking, followed by the use of various manual implements, such as short rakes or tongs. These methods were designed to use in near-shore or intertidal areas where mollusks are found at or near the sediment surface (MacKenzie *et al.* 2002). Fishermen developed longer rakes (e.g., bull rakes) and eventually dredges to harvest shellfish in deeper waters or buried more than a few centimeters in the sediment (MacKenzie *et al.* 2002). The following definition of a dredge is excerpted from Stokesbury *et al.* (2011):

> Dredges, typically consisting of a net on a frame towed behind a boat, have been designed to harvest epifauna or infauna, and the configuration of the gear varies greatly depending on the target species and the substrate. Some dredges skim the surface of the seabed while fishing as exemplified by offshore sea scallop (*Placopecten magellanicus*) fishery. Other dredges utilize hydraulic jets, toothed rakes, or suction apparatus to harvest shellfish located within the sediment. Mechanical harvest of cultured shellfish is typically done with a rake-like device with a trailing bag to collect the catch. They remove molluscan shellfish from the seabed, and they are also used to harvest crustacean, finfish, and echinoderms.

None of this should be confused with channel dredging, which is used to deepen or widen waterways by removing sediment. Dredges used to harvest shellfish are designed to capture shellfish, leaving the sediment behind.

Dredges can be further defined as to whether pressurized water is used to aid in harvesting, referred to as hydraulic, or not, referred to as mechanical. The rocking-chair dredge was developed in Massachusetts in 1945 to harvest hard clams (MacKenzie *et al.*, 2002; Mercaldo-Allen and Goldberg, 2011). The mechanical device was approximately two feet wide with teeth that measured seven inches in length and could operate in water depths of 12 to 25 feet. A chain bag that held a volume of about eight bushels was attached to the back to collect clams (MacKenzie *et al*., 2002). By the 1950s, hydraulic dredges were developed in New York and Connecticut to harvest surf clams and ocean quahogs, respectively, replacing the less efficient rocking-chair dredge (MacKenzie *et al.*, 2002; Mercaldo-Allen and Goldberg, 2011; Parker, 1971). Typically, a hydraulic dredge consists of a boat-mounted pump that supplies pressurized water through nozzles, which are attached to a dredge head (defined as a hydraulic manifold and blade), to loosen mollusks from sediments. In early designs, a bag connected to the dredge was used to collect shellfish after the dredge blade passed under the sediment (MacKenzie *et al*., 2002). In 1954, fishermen from Maryland improved upon this design by increasing the depth to which the water penetrated the sediments (18 inches in some cases) and adding a metal mesh belt, or escalator, to move clams from the dredge to the deck of the boat, where sorting could easily occur (Godcharles, 1971; MacKenzie *et al.*, 2002; Mercaldo-Allen and Goldberg, 2011; Rheault, 2008; Tarnowski, 2006). The escalator dredge was modified later by Canadian fishermen to harvest soft shell clams in shallow water on intertidal flats.

Hydraulic dredges can vary in design, size, and weight depending on the target species, sediment type, and area being fished (Mercaldo-Allen and Goldberg, 2011). Hydraulic dredges are used to harvest soft clams, hard clams, oysters, sea scallops, surf clams, and ocean quhogs (Coen, 1995; Mercaldo-Allen and Goldberg, 2011). In Long Island Sound, naturally seeded hard clams are harvested by hydraulic dredges from leased shellfish beds in 10-16 feet of water. This extensive cultivation practiced in Connecticut supports a multi-million dollar industry ($17M reported in 2010). The dredges used measure from 2 to 4 feet in width and weigh from 400 to 900 pounds (Goldberg *et al.*, 2014). The typical dredge used to harvest ocean quahogs and surf clams in offshore waters is 12 feet wide and about 22 feet long (Stevenson *et al*., 2004). Another type of hydraulic dredge used to harvest sea scallops off of George's Bank is approximately 14 feet wide and weighs about 2,200 pounds (Stevenson *et al.*, 2004). The pumps, which supply pressurized water to these hydraulic dredges, range from 50-400 horsepower (hp) (Lambert and Goudreau, 1996; MacPhail, 1961a; McCrae and Daniels, 1998; Smolowitz and Nulk, 1982).

Hydraulic dredges remove and re-suspend the top layer of sediments, affecting the harvest site, water column, and depositional area. Harvesting effects from the use of dredges have been examined, but most studies conducted are either gear- or site-specific. The quantification of these effects has recently been compiled into several literature reviews (Mercaldo-Allen and Goldberg, 2011; Rheault, 2008; Tarnowski, 2006). Research summarized in these reviews show that harvesting shellfish with hydraulic dredges results in variable, but temporary site-specific, changes to bottom substrates and benthic communities (Coen, 1995; Mercaldo-Allen and Goldberg, 2011; Tarnowski, 2006). In one study, plumes generated from hydraulic dredging had higher turbidity than background levels; the change in concentration of suspended sediments was rapid as larger particles, such as sand, were suspended for a limited time before settling within or near the dredge tracks (Ruffin, 1998). Finer particles, such as silt and clay, remained in the water column for longer periods of time. In some cases, elevated turbidity and sediment plumes extended up to 75-100 feet beyond the harvest sites (Mercaldo-Allen and Goldberg, 2011). Rheault (2008) reported 98 percent of suspended sediments settled to the bottom within 50 feet of the harvested site, while Mercaldo-Allen and Goldberg (2011) reported suspended sediments dispersed within 30 minutes to 24 hours after harvesting. In another study, the maximum distance dredge effects were discernable was 15-75 feet from the harvest site (Tarnowski, 2006). In all studies, re-suspension, turbidity, and deposition were affected by soil grain size, type, and hydrologic conditions specific to a particular harvesting site (Barnes *et al*., 1991; Coen, 1995; Rheault, 2008).

Another impact to sediments by the use of hydraulic dredges is the formation of a track or trench. The width of the track is generally equal to the width of the dredge (Tarnowski, 2006). Trench depth is a product of how deep the harvester is allowed to dig into the sediments. For example, a hydraulic dredge designed for coastal bays in Maryland was set to cut 2.5-4 inches below the surface of the substrate, leaving behind a trench that was four to eight inches deep (Tarnowski, 2006). Dredge tracks created by a small (four feet wide) hydraulic dredge used to harvest surf clams in New York were characterized by smooth shoulders, angled walls, and a flat floor (Meyer *et al.*, 1981). Although the tracks were initially noticeable, they began filling almost immediately. Total recovery time has been reported to vary from hours to months and was dependent on sediment type, grain size, and local hydrologic conditions (Mercaldo-Allen and Goldberg, 2011). In addition to creating tracks, Pftizenmeyer *et al*. (1972) found that sediment compaction was reduced for up to a year using a hydraulic clam dredge, but in areas with medium and fine sand bottoms, grain size did not differ after harvest. Changes to soil grain size and transfer of suspended sediments were reported as minimal when compared to natural seasonal disturbances (Godcharles, 1971; Godwin, 1973).

Hydraulic dredging not only affects physical parameters, but biological ones as well. Organisms removed from the soil by dredging were found to be either killed immediately, entrained in the hopper (catch basket), or redistributed elsewhere with or without damage (Tarnowski, 2006). Young, soft-bodied organisms were more susceptible to direct dredge effects and burial from deposited sediments. Although these effects have been documented, several studies have shown that actual damage and mortality rates were lower than hand methods (Coen, 1995; Kyte and Chew, 1975). In several studies, benthic recovery from dredging was affected by natural seasonal changes within the water column and substrate, as well as reproductive patterns and life cycles of the benthic organisms (Hall and Harding, 1997; Langton and Auster, 1999). Furthermore, changes in benthic community structure were more clearly associated with seasonal variability than dredging, suggesting that dredging effects are minor in scale and impact (Alves *et al*., 2003; Godcharles, 1971; Sparsis *et al*., 1993).

Another device of interest to this discussion is the hydraulic rake, which was developed in Canada to help fishermen harvest clams in shallow intertidal flats (Mercaldo-Allen and Goldberg, 2011). Although called a rake, most of these devices do not have tines or teeth, but instead a series of nozzles that push water into the sediments. Like a hydraulic dredge, the rake uses pressurized water to dislodge clams by causing the upper strata of the soil profile to change from a solid state to a liquid one (MacPhail, 1961b; MacPhail and Medcof, 1962; Nickerson and Brown, 1979). Clams rise to the soil surface from an increase in the specific gravity of the sediment/fluid mixture. Unlike a hydraulic dredge, collection of clams is either by hand or rakes. Variations of this hand-operated, pump-driven device have been used to harvest bottom-planted and wild clams in Canada, Italy, Alaska, and Virginia (Medcof and MacPhail, 1964; Munari *et al*., 2006; Nickerson and Brown, 1979). Most of the early research on these harvesting devices focused on operation and production parameters. In two studies, clam farmers harvested areas at rates of 8-10 $ft^2$/min (Medcof and MacPhail, 1964) and 44-82 $yd^2$/hr (Bourne, 1967). Harvesting efficiency, or removal of clams in a given area, was reported as 85 to 95 percent. Damage to both harvested clams and those remaining in the soil was reported as <5 percent (Bourne, 1967; MacPhail and Medcof, 1962). More recently, studies have examined benthic community responses to this type of device. In a comparative study between three types of rakes (manual, hydraulic, conveyor), effects to the benthos by the hydraulic rake were negligible and similar to the manual rake, whereas the conveyor rake resulted in more deleterious effects, such as larger and prolonged reduction of species abundance and diversity (Munari *et al*., 2006). Disturbances to the benthic community by either the hydraulic rake or manual rake were considered as having no lasting consequences as recolonization by small infaunal species was relatively rapid within the time frame of the experiment (27 days). However, no studies have addressed how the use of these harvester devices would affect subaqueous soil properties that are known to influence benthic communities.

A previous study conducted in the Indian River highlighted the need for a "low turbidity" shellfish harvester in Florida (Stewart and Vaughn, 1989). This is the only example in the literature of mechanical harvesting bottom-planted clams in the state. A suction harvester was tested, which used a 5 hp engine and a 2" water pump to produce enough suction from a venturi device for lifting the clams through a discharge pipe. A bushel basket or mesh bag was attached to the discharge to collect the harvested clams and allow water, sediment, and other debris to fall through. In the study, the suction harvester was compared to treading and manual raking. Use of the suction device increased turbidity, but values measured 30 minutes post-harvest were comparable to the other techniques examined. Suspended sediment loads were also greater for the suction harvester; however, 60 minutes post-harvest, winds caused suspended sediment loads outside the silt curtain (used to contain sediment transport) to equal those inside. As noted previously, weather events and other natural forces can produce effects to bottom substrates and suspended sediments that are comparable to or exceed harvesting effects.

The pump-driven "box" harvester evaluated in this study (see pages 7-8 for a detailed description) is most similar to the hydraulic rake in size and design. However, the means of collection differ as the pump-driven harvester has a detachable basket. Since there is little information on the effects of water and soil physiochemical properties using this type of harvester device, the effects caused by hydraulic dredging were reviewed in this section. The main difference between hydraulic dredges and the 5 hp pump-driven harvester evaluated in this study is the scale of operation as the latter weighs less than 80 pounds and is only two feet in width.

## Rationale/Justification/Applicability to Florida's Aquaculture Industry

The United States shellfish farming community has recognized the need to examine farming practices, such as mechanical harvesting, to ensure sustainability of natural resources (e.g., water quality, submerged lands, fisheries) and their own economic viability (Shumway *et al*., 2003). Likewise, the Florida Clam Industry Task Force requested in 2012 that research on alternative harvesting methods, which would minimize impacts to these resources and potentially improve clam production, be conducted. The prohibition of mechanical harvesting on shellfish aquaculture leases has Florida growers limited to manual methods (hand raking) that may not be commercially viable or acceptable to the industry. In order to obtain full adoption of sunray venus culture by industry, this work focused on providing science-based information to eliminate statutory and/or regulatory barriers to production that serve as constraints in establishing this species and other potential aquaculture species as feasible complements to hard clams. In addition, recent USDA and NOAA-funded projects addressed the need for increased summer survival of cultured hard clams in Florida by identifying biomarkers of thermal tolerance for use in selective breeding (Baker *et al*., 2011). This problem may be ameliorated by the seasonal use of bottom planting. Hard clams reaching market-size (the size most affected by heat stress) during the summer would be able to bury deeper into the bottom substrate, or soils, during periods of environmental stressors. To meet increasing national and global demand for aquaculture products, the hard clam industry, whose product sells for pennies at the farm and is faced with increasing production costs (e.g., fuel), must increase yield, efficiencies, and profitability. Therefore, to advance the shellfish aquaculture industry, the environmental effects of mechanical harvesting on bottom-planted bivalve mollusks were examined.

This study directly addressed a research priority identified by the Florida Aquaculture Review Council in their 2013-14 Request for Statements of Interests. Further, the 2012-2013 Florida Aquaculture Plan stated "that innovations in culturing new species and development of new technologies to manage operations with maximum efficiency will ensure Florida's aquaculture industry remains competitive in today's global economy." The sunray venus clam was also specifically identified as a candidate species for research. Responsibilities of the Florida Department of Agriculture and Consumer Services (FDACS), Division of Aquaculture include administering the lease program for the state. Results from this research could assist the Division in consideration of seeking approval for the use of pump-driven harvesting devices on shellfish aquaculture leases. Based on our findings, recommendations for best management practices on the operation of pump-driven harvesting devices could be made and included in rule (Chapter 5L-3, F.A.C.). In addition, just as agricultural soil science examines soil properties for terrestrial crop selection, subaqueous soils were evaluated in this study for suitability of sunray venus clam culture. In doing so, a soil-based approach was developed and used as a tool in siting leases.

Development of alternative culture species and farming technology represents an important gain over the present reliance of a single species crop. Diversifying the industry will have a positive impact on shellfish aquaculture in Florida by improving production, mitigating production and market risks, diversifying revenue streams, and increasing cash-flow for clam farmers and ancillary businesses, thereby enhancing economic stability and continued growth. If the use of a pump-driven harvesting device is found to be similar or less disruptive to water quality and soils in lease areas as harvesting bottom bags, then a different culture method for bivalve species would be available to the industry. If bottom planting is adopted by industry, then the culture of species that are not amenable to bag culture would be made possible. If barriers to the culture of alternative species, bottom planting and harvesting are eliminated, then there is great potential for economic expansion of the shellfish aquaculture industry in Florida.

## Objectives

The goal of this project was to evaluate alternative growout culture and harvesting methods that may eliminate barriers to commercialization of a promising aquaculture species, the sunray venus clam, and facilitate technology transfer to the Florida hard clam culture industry. To achieve this goal, the project team hypothesized that the effects of harvesting bottom-planted sunray venus clams with a pump-driven device would be similar or less disruptive to those associated with harvesting bottom bags. Due to the site-specific nature of harvesting gear effects, this study examined the relationships between the use of a pump-driven harvester and water quality and soil physiochemical properties on the west coast of Florida.

Objectives of this project were to:
1) Examine production characteristics of sunray venus clams using bottom net culture,
2) Assess the product quality of sunray venus clams harvested by two methods,
3) Determine the effects on water and soil physiochemical properties resulting from the use of a pump-driven device to harvest bottom-planted sunray venus as compared to harvesting bottom bags, and
4) Evaluate suitability of commercial leases for sunray venus clam production using a soils-based approach.

## Materials and Methods

*Production Characteristics of Sunray Venus Clams using Bottom Net Culture*

Growout-sized sunray venus clam *Macrocallista nimbosa* seed (n=36,000) obtained from a Florida Sea Grant-funded project were bottom planted in quadruplicate under cover nets (8’ x 10’, 80 $ft^2$) and in 9 mm polyester mesh growout bags (5 bags belted per replicate, 16 $ft^2$ per bag or 80 $ft^2$ per belt). Each culture method was stocked at a density of 56/$ft^2$ (4,500 per bottom plant, 900 per bag or a total of 4,500 per belt) during November 2012. The bottom cover netting consisted of a layer of 9 mm mesh polyester material covered with ½” mesh high density polyethylene, the perimeter of which was staked to the bottom and further secured with ½” rebar. The field trials were conducted on the UF management use agreement (38-MA-1106) located in the Dog Island High-density Lease Area near Cedar Key. Water quality data (temperature, salinity, dissolved oxygen) at the growout location was measured continuously with a YSI 6600 sonde.

A pump-driven harvesting device, referred to as a "box" harvester and used by Virginia clam growers, was purchased and used to harvest bottom-planted sunray venus clams. The device is box-shaped, welded from stainless steel, weighs about 78 pounds, and measures 17" long by 24" wide along the spray bar, with a mouth opening of 2.6 $ft^2$ in the front decreasing to 1.75 $ft^2$ in the rear. It does not have tines, rather the bottom of the box mouth opening is set at a 30° angle to aid in digging. The harvester is pulled manually by the operator at water depths ranging from 10 inches to around 3 feet. A 5 hp pump delivers pressurized water through 18 nozzles (17/64" diameter) along the spray bar, which agitates and fluidizes the soil. This dislodges the clams, allowing them to rise to the soil surface. The box "digs" into the soil and shunts material to the back, where a removable wire-mesh basket collects the clams and allows soil particles to pass through. The 2.9-$ft^3$ collection basket can be covered with vinyl-coated wire of various mesh sizes, depending on the harvest size of the clams.

*Pump-driven harvester, or box harvester, evaluated on bottom-planted sunray venus clams*

Harvesting of the four replicated bottom plants and bottom bag belts began the week of 21 October 2013 (Figures 1 and 2). Due to the amount of effort involved with water quality sonde (n=9) deployment, retrieval, and maintenance for each replicate, the harvests were scheduled biweekly to coincide with spring or neap tides. The last harvest occurred during the week of 16 December 2013. This resulted in a culture period ranging from 11-13 months (average of 12 months), the time period previously determined for sunray venus clams to reach ~50 mm (2") shell length in bottom bags (Sturmer *et al*., 2009). At harvest, live sunray venus clams from each culture method were counted to obtain survival estimates as well as sorted on 7/8" and ¾" bar graders to determine potential market size frequencies. Growth characteristics measured for sunray venus clams harvested from each culture method included shell length, shell width, total weight, and shucked meat (wet) weight. Twenty to two hundred sunray venus clams per replicate were used for each parameter measured, depending on the parameter. Presence of predators and fouling organisms was also noted during harvest. Survival and growth data were analyzed using appropriate statistical tests after testing data for underlying assumptions. As the data met the assumption of normality, transformations for analysis were not performed. Overall averages for the two culture method treatments were compared with a t-test analysis using PROC TTEST in SAS software, version 9.4. Statistically significant differences were identified at $p<0.05$.

*Product Quality of Sunray Venus Clams Harvested by Two Methods*

Product quality of harvested sunray venus clams was assessed to determine the effects of both culture and harvest methods on shell deformities, shell breakage, meat grittiness after harvest and purging, and shelf life in refrigerated storage.

*Shell deformity in a cultured sunray venus clam*

Shell Deformities Shell deformities, or irregularities, of sunray venus clams cultured in bottom bags have been observed (Sturmer *et al*., 2009). The deformities were limited to the ventral margin (shell lip) with one valve (shell) usually having excessive curvature, resulting in a depression (or indentation) of the shell. This caused the shell lips not to meet in some of the clams, leaving a visible opening. Shell deformities quantified in a 2007-8 gear trial ranged from 0.5-3.7 percent in bags with internal PVC pipe frames to 19-22 percent in bags without frames. In this study, shell deformities were noted during the measurement of sunray venus clam samples for growth characteristics.

Shell Breakage In our literature review, damage to hard clams harvested by a hydraulic rake was reported to be low (<5%). Shells of sunray venus clams are thinner than hard clams of equal size. However, in our experiences with handling sunray venus clams during harvesting of bags and processing (e.g., tumbling and grading), we have observed little shell breakage. To quantify shell breakage associated with harvesting bottom plants and bags, sunray venus clams observed to be broken, cracked, or crushed during the sorting of clams for survival estimates were set aside and counted. Shell breakage was expressed as a percentage of the total number of live clams per culture and harvest method. Both shell deformities and breakage were analyzed by t-tests (PROC TTEST, SAS software, version 9.4) to determine differences between harvest methods.

Meat Grittiness A science-based sensory profile was developed to characterize sunray venus clams produced through aquaculture (Garrido and Otwell, 2011), as was done for hard clams and oysters (Garrido *et al*., 2007; Garrido *et al*., 2009; Otwell *et al*., 2012). A negative characteristic determined for all molluscs is the presence of sand or grit in the meats, which results in an unpleasant and negative mouth-feel. In the sensory characterization of sunray venus clams, grit was detected in some samples with values ranging from 0.25 to 1.5 on a 5-point intensity scale (Garrido and Otwell, 2011).To determine if mechanical harvesting had an effect on this sensory attribute, samples of sunray venus clams from bottom plants and bottom bags were collected after harvest for two replicates (October and November harvests). Half of the samples were placed in wet storage at the UF Shellfish Aquaculture Research Facility, where they were purged in running salt water from conditionally approved shellfish harvesting waters for 24 hours. The remaining half were evaluated by agency staff located at the Senator Kirkpatrick Marine Lab in Cedar Key, who previously agreed to serve as panelists in this taste test. Sunray venus clam samples were cooked in a microwave (about one minute) until the clams opened. Samples were presented to 10 panelists using blind codes. Each panelist was asked to consume five clams per sample and then report their average ratings based on a 5-point intensity scale, where a value of 0 indicated “not gritty,” a value of 1 indicated “slightly gritty,” a value of 2 indicated “moderately gritty,” a value of 3 indicated “very gritty,” and a value of 4 indicated “extremely gritty.” In the second evaluation, another sample of sunray venus clams, which was purged for 48 hours post-harvest, was included. Ratings from both replicate evaluations were averaged by panelist for each culture method and purging duration. Average ratings were then analyzed by t-tests with PROC TTEST in SAS software version 9.4 to determine differences in grittiness between culture/harvest methods after 0, 24, and 48 hours of purging. Average ratings were analyzed to determine within culture variation in grittiness over time by t-tests for the first replicate and general linear model (PROC GLM) and Tukey's HSD test for the second replicate due to the additional purging time period.

Shelf Life Molluscan shellfish are typically shipped as live shell stock and adequate shelf life is an important product attribute. Federal and state regulations require that live mollusks be placed in refrigerated storage within a predetermined time/temperature harvest matrix in order to reduce probable levels of *Vibrio* bacteria (FDA, 2009). For these reasons, shelf life of live sunray venus clams harvested by both methods was investigated to assure product quality and safety. Three samples of 100 live sunray venus clams harvested from a bottom plant and an equal number of samples from the combined harvest of five bottom bags were packaged in polyethylene harvest netting. The samples were obtained from similar sized sunray venus clams after grading. Samples were tempered at ~70-72°F for approximately six hours, then transferred to a refrigerated cooler and maintained at the standard storage temperature of ≤45°F. Each sample bag was checked for survival and gaping every other day for 10 days. Two shelf life evaluations were conducted using sunray venus clams harvested in October and December (2013), when ambient water temperatures at harvest were 74°F and 59°F, respectively, to determine if differences in survival and gaping were associated with culture methods.

Gaping When removed from water, molluscan shellfish open their valves (shells) as a stress response to "test" their environment; this response is referred to as gaping. Gaping also allows mollusks to utilize atmospheric oxygen for respiration. Visual judgments were used to assess gaping of sunray venus clams during the shelf life evaluations. Gaped sunray venus clams were considered alive when they responded by closing their shells to specified agitation, or tapping, after the sunray venus clams were held for a short time at room temperature. Both survival and gaping data were averaged by culture method and analyzed by repeated measures ANOVA using PROC MIXED and least significant difference tests (SAS software version, 9.4) for each shelf life evaluation.

*Effects on Water Quality and Soil Properties using a Pump-driven Harvest Device*

According to Stokesbury *et al*. (2011), designing a statistically defensible experimental study that comprehensively evaluates harvesting effects requires direct comparison of dredged areas to undredged areas in close proximity that have similar habitat, environmental, and hydrodynamic properties. To address this, a Before-After, Control-Impact, Paired (BACIP) sampling design was employed to examine effects of culture methods and harvesting practices on various parameters, and to differentiate natural changes from those caused by harvesting (Smith, 2002; Stewart-Oaten *et al*., 1986). The main premise of a BACI design is that anthropogenic actions alter the environment, so that it differs from its original state prior to disturbance and from changes occurring at control sites during the same time (Mercaldo-Allen and Goldberg, 2011; Underwood, 1992). Reference and experimental sites are located in close proximity (10-20 feet) to each other to control for parameters, such as water depth, substrate type, and benthic community structure (Collie, 1998; NRC, 2002). Shellfish farming activities at commercial leases occur on a near continuous basis with nominal fallow times (<1 month). Wilber *et al*. (2008) reported that in areas subject to repeated disturbances, recovery of benthic assemblages to pre-harvesting conditions was not a practical expectation. For these reasons as well as limitations in a one-year study, we did not sample infaunal benthos.

Water Quality To investigate potential differences between water quality disturbances, associated with the harvest methods and to differentiate natural changes from those caused by harvesting, nine YSI 6600 sondes were deployed in cardinal directions five feet from the perimeters of both the bag and bottom plants with one sonde placed midway between the culture units, which were planted 10 feet apart; additional sondes were placed 25 feet down current of both culture methods (Figures 3 and 4). Multiple parameters (water temperature, salinity, dissolved oxygen, and turbidity) were measured continuously (every minute) for a period spanning 48 hours pre- and post-harvest. It was decided to treat each harvest replicate as an independent evaluation as ambient conditions (tide, current, wind, and background turbidity levels) were different under each harvest activity. Water quality parameters with the exception of turbidity were summarized (mean, standard deviation, minimum, maximum) for all replicates per sonde location.

To investigate potential differences in harvesting techniques with respect to turbidity, each of the four replicate harvests was analyzed statistically for differences between background conditions and harvest treatments, as well as differences between the pump-driven harvester and the traditional bag harvest technique. Mean turbidity values within each replicate and then among replicates were compared with student's t-tests ($p<0.05$) to determine significant differences. Because of the inherently high variability in the environmental conditions which can affect turbidity levels during experimentation, maximum observed values were compared using the same statistical techniques. The mean turbidity 30 minutes prior to harvest activity was used to define the background condition (Figure 5). To determine the return interval, defined as the time it takes for turbidity to return to background condition, turbidity measurements of post-harvest activity were monitored and the time at which the background condition was reached recorded. In some cases, environmental conditions increased turbidity during the course of conducting the replicate harvest. In these cases, the changing baseline was subtracted from the post-harvest turbidity values to remove the increasing trend in observations and thus accurately determine the return interval (Figure 5).

Commercial-Scale Harvest Trial To determine the extent of a sediment plume created by the use of a pump-driven harvester in a commercial-scale application, an unfarmed area (without sunray venus planted) of 300 $ft^2$ (25' by 12' plot) was tested within the UF experimental lease. The size of the "mock" harvest area was determined by assuming a harvest of 10,000 sunray venus clams, 60% survival at harvest, and a planting density of 56 per $ft^2$ (the same density used in the field trials). Eleven YSI 6600 sondes were deployed to measure turbidity continuously (every minute) for 48 hours (24 hours pre-and post-harvest) and assess the concentration of suspended particles in the water column. Sondes were located at three distances from the harvest area (Figure 6). Four sondes were positioned 5 feet from the mid-points of the test plot to the north (N-5), south (S-5), east (E-5), and west (W-5). Another four sondes (N-25, S-25, E-25, W-25) were positioned 25 feet from the mid-points of each side of the test plot. Three sondes were deployed 45 feet to the south of the plot with the middle sonde (S-45) located in-line with the sondes positioned at 5 and 25 feet intervals and the other two sondes located 20 feet to the east (SE-45) and west (SW-45). Tidal and wind data were obtained from a NOAA station 8727520 located at the city dock in Cedar Key, Florida, approximately 1.5 miles west of the UF experimental lease. Current velocity was measured using a low-velocity mechanical flowmeter (General Oceanics); water depth was obtained from on-site measurements.

Soil Characteristics Prior to planting sunray venus clams, three soil cores (10 cm diameter, 10 cm deep) per bottom plant and bottom bag belt replicate were collected to establish baselines for soil properties (particle size distribution, organic matter content). At harvest, an additional three soil cores per culture method replicate were collected to compare soil properties with those established at planting; three cores were also collected at reference (unfarmed) sites located between the culture sites (Figure 7). Sampling occurred repeatedly post-harvest at four and eight weeks to evaluate changes in soil properties over time. Soil cores were collected from the northern, middle, and southern sections of each treatment and reference replicate site during each sampling period. Exact coring locations varied within those areas to ensure that collected soils were reflective of recovery from harvesting and not previous coring efforts. Soil disturbance was minimized by taking the most direct route to sample locations. Soil cores were transported to the UF Pedology and Minerology Laboratory in Gainesville for analyses of soil physical and chemical properties. Soil core samples were extracted, oven dried at 100$^{o}$C, and weighed to determine bulk density. Particle size distribution (PSD) and organic matter (OM) content were determined on the oven-dry samples. The PSD was determined by settling via the pipette method (Soil Survey Staff, 1996); the OM content was estimated by weight loss after ignition (Donkin, 1991). For the baseline analysis, silt and clay size fractions of soils were grouped together and referred to as fines. Soil properties were averaged for each culture/harvest method and reference replicate. T-tests (PROC TTEST, SAS Software, version 9.4) were employed to determine if significant differences ($p$<0.05) existed between soils prior to planting and reference sites at harvest. Repeated measures ANOVA (PROC MIXED, SAS software, version 9.4) were used to detect significant changes in soil properties between and within culture/harvest methods. Tukey-Kramer post-hoc tests were used to detect significant variation in soil property means between culture and reference sites. All percentages were arcsine transformed prior to analysis and then back-transformed for presentation purposes.

Harvest Track Depth and Recovery Cross-sectional soil elevation profiles were monitored to capture tracks created by bottom plant and bottom bag harvest activities. To accomplish this, an array of PVC pipes was pushed into the soil to a given depth (approximately 2 feet), perpendicular to the track direction following harvest (Figure 8). Each array was positioned so that three PVC pipes were located within the depressions created by harvesting the bottom bags and eight pipes were located within the tracks created by the pump-driven harvester at bottom plant sites. In addition, two reference pipes were located in unfarmed areas, 1.5 feet outside of the tracks to either side. Two pipe arrays were deployed at each bottom bag and bottom plant replicate. During deployment, foot traffic was limited to the south side of the pipe array. To detect changes (or infill) in the harvest tracks and assess recovery of the soils to the reference conditions, soil elevations were monitored over time (0, 4, and 8 weeks post-harvest) by measuring the length of PVC pipe exposed above the soil surface. Every possible effort was made to minimize disturbance to soils when measuring elevations; for example, we remained on the south side of the pipe arrays and soil elevations were measured to the north. To create the soil elevation profile immediately post-harvest, the height of each pipe in a row was subtracted from the height of a reference pipe (eastern location). Differences in height between the reference pipe and other pipes within the row represented topography changes immediately post-harvest. Beginning with week 4, the amount of soil infill or loss (differences between week 0 and subsequent sampling efforts) was added to week 0 soil elevations to determine values at 4 and 8 weeks post-harvest. The difference between reference and treatment elevations within a row were then averaged by replicate for each week ($n$=4/replicate/week). Data were analyzed with repeated measures ANOVA (PROC MIXED method, SAS software, version 9.4) and results considered significant at $p<0.05$. Tukey-Kramer post-hoc tests were used to detect changes in soil elevations between harvest methods by week.

*Suitability of Leases for Sunray Venus Clam Production*

To assist interested growers in determining if their lease sites were suitable for sunray venus clam production, subaqueous soil properties (particle size distribution and organic matter content) were analyzed and interpreted. Soil "test kits" were assembled for growers to collect samples from their leases. The kit consisted of the following materials: 8" section of 2"-D PVC pipe, 2"-D PVC caps, quart and gallon-size Ziploc® bags, and pre-paid addressed shipping box. Two forms were developed and sent with the soil test kit - *Subaqueous Soil Sampling and Testing Fact Sheet* and *Subaqueous Soil Test Form* (Appendix A). Growers, who expressed interest in culturing sunray venus clams, with leases in Brevard, Indian River, Manatee and Volusia Counties were contacted. These growers received priority as leases in other areas (e.g., Franklin, Levy, and Lee Counties) were evaluated in a prior Florida Sea Grant-funded project.

## Results and Discussion

*Production Characteristics of Sunray Venus Clams Using Bottom Net Culture*

The size of sunray venus clams ($n$=50) at plant averaged 25.4 ($\pm$1.2) mm in shell length, 8.6 ($\pm$0.3) mm in shell width, 15.2 ($\pm$0.6) mm in shell height, and 2.4 ($\pm$0.3) grams in live (total) weight (Table 1). During the growout period of approximately 12 months, water temperatures and salinities averaged 72.2 ($\pm$10.7) $^{o}$F (22.3 $\pm$ 5.9$^{o}$C) and 25.8 ($\pm$2.8) ppt, respectively. Production characteristics (survival and growth) per culture method treatment of sunray venus clams at harvest are presented in Table 2. Survival was not statistically different ($p$=0.86) between culture methods. The average survival of sunray venus clams cultured in bottom plants and bottom bags was similar at 47 and 48 percent, respectively. Shells of dead sunray venus clams retained by the pump-driven harvester and contained in the bottom bags were evaluated to assess when mortalities occurred. Sunray venus shells with lengths greater than 40 mm were assumed to be of potential market size. On average, 757 sunray venus clams per bottom plant were greater than 40 mm and 426 were less than 40 mm. If the bottom plants had been harvested earlier than 12 months, an additional 18 percent of the sunray venus clams could have been marketable increasing survival to 66 percent. In contrast, an average of 293 shells of sunray venus clams harvested from the bottom bags had lengths greater than 40 mm and 638 were less than 40 mm. Using the same assumption as above, an additional 8 percent of the sunray venus clams cultured in bottom bags could have reached market size with survival increasing to 57 percent. Moon snails *Neverita duplicata* were the dominate predator observed at harvest with 11-15 snails obtained per bottom plant. The number of shell irregularities and discoloration observed of sunray venus clams harvested from the bottom bags suggested that the bags did not bury completely (Figure 9).

Growth characteristics of sunray venus clams differed significantly ($p<0.01$) between the two culture methods. Average shell length (SL) and shell width (SW) of sunray venus clams harvested from the bottom plants were 62 mm and 21 mm, respectively, resulting in sunray venus clams 29 percent larger in shell length and 12 percent larger in shell width than those harvested from bottom bags (averages: 48 mm SL, 19 mm SW). Sunray venus clams were also graded at harvest, which is a function of shell width. On average, 33 percent of the sunray venus clams harvested from bottom plants and 4 percent of those harvested from bottom bags were retained on a 7/8" bar grader, whereas 64 percent of the sunray venus clams harvested from bottom plants and 41 percent of those harvested from bottom bags were retained on a 3/4" bar grader. Greater differences were observed between the two culture methods pertaining to harvest weights. Average total weight (TW) and meat (wet) weight (MW) of sunray venus clams harvested from bottom plants was 30 grams (15/lb) and 8 grams, respectively, resulting in clams 73 percent heavier in total weight and 76 percent heavier in meat weight than those harvested from bottom bags (averages: 17g TW [27/lb], 5g MW). Yields were calculated based on average survival and total weight of the sunray venus clams harvested per culture method. Yields were significantly greater ($p=0.01$) from the bottom plants than the bottom bags (1.8 versus 1.0 lbs/ft$^2$), resulting in an 80 percent increase in production.

Sunray venus clams cultured using the bottom plant method grew faster and were more uniform than those cultured in bottom bags (Figure 10). Using the bottom plant method, the culture period to obtain a potential market size of about 50 mm (2") shell length may be reduced by 2-3 months. Reducing the culture period by 15-25 percent may also lessen the risks associated with mortalities due to predation or adverse environmental conditions, resulting in higher crop survivals. However, the incentive for growers to use bottom plant culture methods for sunray venus clams will be limited by the prohibition of mechanical harvesting (even pump-driven devices such as the harvester evaluated in this study) on shellfish aquaculture leases.

*Product Quality of Sunray Venus Clams Harvested By Two Methods*

<u>Shell Deformities</u> An average ($\pm$SD) of 3.1 ($\pm$0.9) percent of the sunray venus clams sampled from bottom bags were deformed, whereas only 0.5 ($\pm$1.0) percent of the sunray venus clams sampled from bottom plants were deformed (see Figures 9 and 10). These means were statistically different ($t=3.99$, $p=0.01$). In previous studies, shell deformities of sunray venus cultured in bottom bags ranged from 0.5 to 22 percent. The higher values were usually found to be sunray venus clams that did not bury into the substrate or that soil properties at the culture site were unfavorable (Ellis and Osborne, 2011; Sturmer *et al*., 2009).

<u>Shell Breakage</u> The average shell breakage ($\pm$SD) of sunray venus clams harvested from bottom bags was 0.5 ($\pm$0.4) percent, while the breakage of sunray venus clams harvested with the pump-driven device was 2.9 ($\pm$2.2) percent. Although the latter value was higher, these means were not statistically different ($t=-2.12$, $p=0.12$). These values fall below those reported in a literature review in which damage to hard clams harvested by a hydraulic rake was <5 percent (Bourne, 1967; MacPhail and Medcof, 1962; Medcof and MacPhail, 1964).

Meat Grittiness Results of sensory evaluations for grittiness in sunray venus clams harvested from both culture methods over two harvest periods are summarized in Tables 3 and 4. Immediately after harvest (0 hours), grittiness of sunray venus clams from bottom bags and bottom plants was similar in both evaluations (first trial, p=0.11; second trial, p=0.34). After 24 hours of purging in the first evaluation, grittiness ratings of sunray venus clams harvested from bottom plants (0.61±0.38) were statistically higher (*p*=0.01) than those harvested from bottom bags (0.22±0.20). In the second evaluation, grittiness ratings after 24 and 48 hours of purging for sunray venus harvested from bottom bags (24 hrs, 0.40±0.53; 48 hrs, 0.31±0.36) and bottom plants (24 hrs, 0.51±0.44; 48 hrs, 0.27±0.27) were similar (24 hrs, *p*=0.63; 48 hrs, *p*=0.79).

Reduction in grittiness ratings of sunray venus clams harvested from both culture methods was significant after purging for 24 hours in both evaluations. In the first, grittiness ratings were reduced by 77 percent (from 0.94 to 0.22) and 59 percent (from 1.48 to 0.61) for bottom bags (*p*=0.006) and bottom plants (*p*=0.003), respectively. In the second, grittiness ratings were reduced by 68 percent (from 1.26 to 0.40) and 70 percent (from1.69 to 0.51) for bottom bags (*p*=0.005) and bottom plants (*p*=0.0001), respectively. Although grittiness ratings in the second evaluation were further reduced after 48 hours of purging for bottom bags (from 0.40 to 0.31, or 22 percent) and bottom plants (from 0.51 to 0.27, or 47percent), results were not statistically significant.

In both evaluations, sunray venus clams harvested from bottom plants had higher grittiness ratings than those harvested from bottom bags. Ratings indicated that sunray venus clams, which had not been purged after harvest, ranged from slightly gritty to moderately gritty. Purging the product for 24 hours resulted in a 69-76 percent reduction in grittiness ratings for sunray venus clams harvested from bottom bags and a 59-70 percent reduction in grittiness ratings for sunray venus clams harvested from bottom plants. Ratings indicated that sunray venus clams, which had been purged for 24 hours after harvest, were either not gritty or slightly gritty. By increasing the purge time to 48 hours, the grittiness ratings were further reduced by 4 percent for sunray venus clams harvested from bottom bags and 13 percent for sunray venus clams harvested from the bottom plant. After which, grittiness ratings of sunray venus clams from both culture and harvest methods were similar (0.27 versus 0.31)

Shelf Life Survival of sunray venus clams in refrigerated storage for 10 days from each culture/harvest method and each evaluation period was 100 percent. Sunray venus clams have been observed to "close up" when moribund (dead) as opposed to hard clams, which remain open when they become weak and die during storage. To ensure that sunray venus clams were alive at the completion of the shelf live evaluations, a knife was inserted into the ventral margin of the valves (shells) of those that were closed to check for resistance, which indicated the animal was alive. Statistical analysis of the survival data was not required. These results exceeded baseline data (90-94 percent survival after 14 days in refrigerated storage under winter harvest conditions) obtained for sunray venus clams during shelf life studies conducted in 2010-11 (Garrido and Otwell, 2011).

Gaping Gaping of sunray venus clams throughout the first shelf life evaluation conducted in October was high, ranging from 25-45 percent for sunray venus clams harvested from the bottom plant and 16-35 percent for sunray venus clams harvested from bottom bags (Table 5). In the second shelf life evaluation conducted in December, gaping was lower with values ranging from 0-8.1 percent for sunray venus clams harvested from the bottom plant and 0.7-9.0 percent for sunray venus clams harvested from bottom bags. Values were similar for both culture/harvest methods and overall lower than those observed in the first shelf life evaluation. This most likely was due to the lower water temperatures at harvest in December.

In the first evaluation, culture method ($p$=0.0001) and time ($p$=0.0008) had significant effects on gaping, whereas only time had a significant effect ($p$=0.003) in the second evaluation. Gaping of sunray venus clams in refrigerated storage did not differ significantly ($p$>0.05) from day 2 to 8 in the first evaluation. By day 10, sunray venus clams harvested from bottom plants exhibited significantly higher ($p$=0.001) gaping (35.4 percent) than clams harvested from bottom bags (19.7 percent). In the second evaluation, gaping of sunray venus clams in refrigerated storage did not differ significantly ($p$>0.05) throughout the ten days.

When time effects were analyzed within each culture method, significant differences were found. In the first evaluation, gaping of sunray venus clams harvested from bottom bags on day 2 was significantly different from day 4 ($p$=0.002), day 8 ($p$=0.006), and day 10 ($p$=0.013). Similar results were observed for sunray venus clams harvested from bottom plants as gaping values on day 2 were significantly different from day 4 ($p$=0.002) and day 8 ($p$=0.018). Differences in gaping of sunray venus clams in refrigerated storage over time were also observed in the second shelf life evaluation. Gaping of sunray venus clams harvested from bottom bags was significantly different between day 2 and day 4 ($p$=0.042), day 4 and day 6 ($p$=0.007), day 6 and day 8 ($p$=0.042), and day 6 and day 10 ($p$=0.033). Similarly, gaping of sunray venus clams harvested from bottom plants differed significantly between day 4 and day 6 ($p$=0.015), day 6 and day 8 ($p$=0.009), and day 6 and day 10 ($p$=0.009).

In summary, product quality of bottom-planted sunray venus clams was not compromised by using a pump-driven harvester device. Shell deformities were significantly lower than those observed of sunray venus clams cultured in bags. Shell breakage associated with harvest methods was similar and less than 3 percent. After purging, grittiness of sunray venus clams harvested by both methods was similar and reduced to acceptable ratings. Shelf life in refrigerated storage was excellent as survival of sunray venus clams from both treatments was 100 percent after 10 days.

*Effects on Water Quality and Soil Properties using a Pump-driven Harvest Device*

Harvest Activities The average time to harvest a belt of five bottom bags (each 16 $ft^2$, or total of 80 $ft^2$) was 10 (±1) minutes, whereas the average time used to operate the pump-driven harvester to collect sunray venus clams from bottom plants (80 $ft^2$ in size) was 49 (±11) minutes. Although these values are quite different, there are intrinsic attributes of the bottom bag culture/harvest method and components of the bottom plant harvest that inflated the time spent using the pump-driven device. The bottom bag is a very efficient method in that it contains the clams, requiring only retrieval from the bottom substrate and washing to remove sediments from the bag. Our familiarity with the use of bottom bags versus lack of experience with bottom plants certainly augmented the time required to harvest sunray venus clams cultured in the latter method. Further, due to the small size of the bottom plant plots, much time was spent turning and repositioning the harvester after pulling it 10’ to cover the length of the area (one pass). After two passes, we had to stop to empty the harvest basket. It required six passes with the harvester to cover the width of the bottom plant, which we will refer to as a harvest set. This effort was repeated three times. The majority of sunray venus was harvested during the first two sets; the third set produced negligible results but was conducted to ensure retrieval of sunray venus clams was complete.

Water Quality Water temperature, salinity, and dissolved oxygen were averaged by replicate and summarized for each sonde location (Tables 6-8). Values are presented for 30 minutes pre- and post-harvest and during harvest of the bottom bags and bottom plants. Water temperature averages at individual sondes ranged from 63.1 to 65.7°F (17.3 to 18.7°C) from 30 minutes pre-harvest to 30 minutes post-harvest. Salinities ranged from 25.9 to 27.7 ppt and dissolved oxygen levels ranged from 5.4 to 7.8 mg $L^{-1}$. Values were consistent at all nine sondes over time. Variation in values between sondes was attributed to acceptable variability of the equipment. Although not statistically analyzed, values measured at the sondes located down current from the harvest areas (south in the first replicate and north for the other three replicates) were similar to those at the other sonde locations.

*Turbidity* The physical process of interest is the agitation of the surface soils and re-suspension of fine particles in the water column, such as silt (0.050-0.002 mm) and clays (<0.002 mm) (Brady and Weil, 2008). Prior to the field replicates, we anticipated the process of using the pump-driven harvester would likely cause re-suspension of silt and clay-sized particles, resulting in both temporary elevated turbidity and a measureable change to the particle size distribution (PSD) in the top 10 cm of soil. Further, we anticipated that both the intensity and duration of turbidity events would be important factors to consider in the evaluation of the harvest methods. The four field replicates occurred on a research lease maintained by the University of Florida that contains soils statistically indistinct from the commercial leases adjacent to the site (Ellis and Osborne, 2011; White *et al*., 2012).

The first harvest replicate was conducted on 23 October 2013, with bag harvest conducted from 9:16-9:25 am followed by pump-driven harvester use from 9:41-10:10am. The tide was falling with a low tide at 11:02 am and average water depth during harvest was 0.67 feet. Winds were light (6-10 knots) out of the north, following the falling tide from north to south; hence, the sondes with greatest chances of capturing turbidity events were S-BB-5 and S-BP-5 (Figure 11-A). In the 30 minutes prior to harvest activities, turbidity ranged from 21.9 NTU (S-BB-5) to 85.0 NTU (E-BB-5) with the greatest 30 minute average response being 60.5 (±19.4) NTU at E-BB-5 (Table 9). Upon initiation of the bag harvest, turbidity values were observed from 31.8 NTU (W-BP-5) to 186.4 NTU (MID) with the highest period mean turbidity observed (74.4 ± 31.0 NTU) at S-BB-5. Bag harvest was followed by use of the pump-driven harvester in which the turbidity ranged from 63.7 NTU (S-BB-5) to 248.5 NTU (S-BP-5) with the highest mean of the period observed (99.8 ± 41.5 NTU) at S-BP-5. The highest mean turbidity for the 30 minute period post-harvest was 81.8 (±34.8) NTU at E-BB-5. No significant difference was found between the average turbidity 30 minutes before harvest and the bag harvest ($p$=0.079); however, there was a significant difference observed between the pre-harvest and pump-driven harvest turbidity ($p$=0.002) with the pump-driven harvester being higher. There was no significant difference observed between harvest methods ($p$=0.194). Pre-harvest was significantly lower than post-harvest turbidity (30 min interval) ($p$<0.0001). We contend that this is due to diminishing tide and wind activity as indicated by the north sondes (N-BP-5 and N-BB-5), which had mean turbidity values of 59.9 (±15.9) NTU and 63.5 (±5.0) NTU, respectively. No significant difference was observed between turbidities from harvest methods in this replicate ($p$=0.194) (Figure 12-A) The return interval, defined as the time it takes to return to a background condition with respect to turbidity, was determined to be 2 minutes for the bag harvest and 9 minutes for the pump-driven harvester (Figure 13). The spatial extent of the turbidity effect was also investigated by comparison of the most active sondes (S-BP-5 and S-BB-5) with the sondes 25 feet away (S-BP-25 and S-BB-25) to determine the distance traveled. In the first replicate, there was no signal noted at the sondes 25 feet away indicating that the turbidity resolved within the 20 feet between these sondes.

The second harvest replicate was conducted on 18 November 2013, with bag harvest from 8:23-8:32 am followed by pump-driven harvester use from 8:35-9:36am. The predicted low tide was at 7:56am, such that incoming tidal flow was from S to N and water depth averaged 0.61 feet during the activity. The wind was out of the southeast at 3-5 knots; hence, the sondes of greatest interest for capturing the turbidity plume from harvesting activities were N-BP-5 and N-BB-5 (Figure 11-B).Turbidity ranged from 4.6 NTU (S-BB-5) to 46.2 NTU (E-BB-5) in the 30 minute interval prior to harvest activities with highest period mean being 30.3 (±4.2) NTU observed at MID (Table 10). During the bag harvest, turbidity ranged from 6.4 NTU (S-BB-5) to 175 NTU (N-BB-5) with highest average turbidity during the bag harvest period observed (60.7 ± 52.1 NTU) occurring at N-BB-5. During the pump-driven harvester activity, turbidity ranged from 4.9 NTU (S-BB-5) to 175.6 NTU (N-BP-5) with the highest average observed (37.2 ± 33.2 NTU) at N-BP-5. In the 30 minute monitoring period post-harvest, turbidity ranged from 7.1 NTU (S-BB-5) to 67.3 NTU (N-BP-5) with the highest average turbidity 30.9 (±1.2) NTU observed at MID. No significant difference was observed between average turbidity of the 30 minute pre-harvest period and the bag harvest ($p$=0.113), the pump-driven harvester ($p$=0.157) or the post 30 minute interval ($p$=0.460). Similarly, there were no significant differences found between harvest treatments ($p$=0.469) or between harvest methods and the post 30 minute monitoring period ($p$=0.245 and $p$=0.338, respectively, for bag and pump-driven harvester treatments based upon average turbidity) (Figure 12-B). Return interval for bag harvest was not determined as it was greater than the time between harvest activities (3 minutes); however, the return interval for the pump-driven harvester was found to be 9 minutes (Figure 14). As there were no sonde response lag farther north than N-BB-5 and N-BP-5, we contend that, similar to the first replicate, there was no spatial impact beyond 25 feet for this replicate.

The third harvest replicate was conducted on 3 December 2013, with bag harvest activities from 9:20-9:31am followed by use of the pump-driven harvester from 9:35-10:34am. The predicted low tide was at 7:01 am so that tide was incoming from S to N during the activity. Winds were SE at 5-8 knots following tidal flow indicating the N-BB-5 and N-BP-5 sondes would have the best chance to capture the turbidity event (Figure11-C). The average depth on site was 0.94 feet rising to 2.7 feet during the activity. Turbidity in the 30 minute pre- harvest interval ranged from 2.0 NTU (S-BP-5) to 40.3 NTU (E-BB-5) with the highest average (31.9 ± 1.2 NTU) observed at MID (Table 11). During the bag harvest, turbidity ranged from 3.6 NTU (N-BB-5) to 130.9 NTU (E-BB-5) with the largest average value being 41.0 (±31.5) NTU observed at N-BB-5. During the pump-driven harvest, turbidity ranged from 8.0 NTU (S-BP-5) to 130.0 NTU (N-BP-25) with highest average value of 53.3 (±17.0) NTU observed at MID. During the 30 minute post-harvest interval, turbidity ranged from 18.4 NTU (N-BP-5) to 56.5 NTU (MID) with the highest average value of 49.0 (±2.4) NTU observed at MID (see Appendix B). Comparison of mean values of turbidity revealed no statistical difference between the pre-harvest and bag harvest periods ($p$=0.065); however, the pump-driven harvester was significantly higher ($p$=0.002) than the pre-harvest period. There was no significant difference found between the turbidity associated with bag harvest and pump-driven harvester ($p$=0.158), between pump-driven harvest and the post-harvest period ($p$=0.766), or between the bag harvest and the post-harvest period ($p$=0.344) (Figure 12-C). Unfortunately, the return interval for the bag harvest could not be calculated due to the temporal proximity of the pump-driven harvest activity; however, the pump-driven harvester return interval was determined to be 5 minutes (Figure 15). There were peaks noted on the N-BB-25 and N-BP-25 sondes suggesting that the spatial impact on this replicate was noted 25 feet beyond the harvest area. Interestingly, there was no lag noted, suggesting that cessation of activity results in a rapid decline in turbidity.

The fourth harvest replicate was conducted on 16 December 2013, with bag harvest occurring from 10:00-10:09am and use of the pump-driven harvester occurring from 10:25-11:00am. The predicted low tide was at 7:09am with an average depth of 0.62 feet of water onsite during activities. Wind was 6-8 knots form the north with incoming tide from the south indicating the N-BP-5 and N-BB-5 sondes would be the best suited to capture the turbidity events (Figure 11-D). During the 30 minute period prior to harvest, turbidity ranged from 7.4 NTU (S-BB-5) to 25.2 NTU (W-BP-5) with the highest mean value 16.5 (± 2.3) NTU observed at S-BP-5 (Table 12). While the bag harvest was ongoing, the turbidity ranged from 7.8 NTU (S-BB-5) to 101.1 NTU (N-BB-5) with the highest average 65.6 (±22.6) NTU observed at N-BB-5. The pump-driven harvest had the highest values observed, which ranged from 6.6 NTU (S-BB-5) to 140.5 NTU (N-BP-5) with the highest average value 52.7 (± 29.6) NTU recorded at N-BP-5. Finally, the 30 minute period post-harvest observations ranged from 9.8 NTU (S-BB-5) to 50.4 NTU (N-BP-25) with the highest average value 23.0 (±5.2) NTU observed at N-BB-25. In this replicate, the bag harvest was found to be statistically indistinct from pre-harvest interval ($p$=0.124) and the post-harvest interval ($p$=0.210). The pump-driven harvester was found to produce significantly higher turbidity compared to the pre-harvest interval ($p$=0.022) but not significantly higher than the bag harvest ($p$=0.669) or the post-harvest interval ($p$=0.228) (Figure 12-D). The return interval was determined to be 5 minutes for the bag harvest and 4 minutes for the pump-driven harvester in this replicate (Figure 16). Because the N-BP-25 sonde recorded a pulse associated with the bag harvest but not the pump harvester, we assert that there was some spatial transport of turbidity in the bag harvest replicate up to 25 feet down current; however, this was not observed during the pump- driven harvest.

*Turbidity – Intensity* Results of the turbidity monitoring indicate that there was measureable re-suspension of small soil particles in the water column resulting in short-term elevations of turbidity in each of the four replicates. Few statistically valid relationships were observed by comparison of mean turbidity values from the four replicates. Noteworthy in the analysis is that in three of the four replicates, pump-driven harvesting created significantly higher turbidity when compared to the pre-harvest condition but exceeded post-harvest condition only one time. This may be due to timing of experimental replicates as the three replicates in which the pump-driven harvest was higher, the tide was rising. In the replicate in which the tide was falling, the pump and bag harvest method did not exceed the pre-harvest condition. Similarly, while the higher levels of turbidity in the post-harvest timeframe may appear to be due to the harvest activities, inspection of timing of the replicates (proximate to low tide or early incoming tide) places the post-harvest observations on the rising side of the turbidity curve associated with incoming tide (see Figure 11). With respect to differences between the harvest methods, there were no significant differences observed between the mean turbidities in any replicate (see Figure 12). In half of the trials, the maximum mean turbidity for the pump-driven harvester is higher than the bottom bag harvest by 12.3-25.4 NTU; likewise for the other half the trials, the bottom bag maximum means exceeded those of the bottom plant by 12.9-23.5 NTU. These findings suggest that both methods are similar in effect when viewing the average sonde measurements. Average measurements from the sonde with the highest detected turbidity were used in this analysis to ensure evaluation of these techniques was based on greatest potential impacts. Comparisons using all data would effectively negate any observable difference among treatments. This assertion, on its own merit, indicates that there is great variability in turbidity in the area where the replicates were conducted and that this natural variability should be viewed in context with the magnitude of the observations.

Many sondes used in the previous analysis did not capture a plume of turbidity during the harvest replicates and their inclusion may skew the results of statistical analyses. To overcome this issue and to ensure that maximum potential effects are identified and viewed in context, a further comparison was conducted that compared the maximum observed values from all replicates grouped by activity (i.e., 30 min pre, bag harvest, bottom plant harvest, 30 min post) (Table 13). The maximum observed turbidity associated with the bag harvest was 186 NTU compared to 248 NTU for the pump-driven harvester. Overall, results indicate that 66% of the turbidity values, which occurred during operation of the pump-driven harvester, were more intense than during the harvest of bottom bags. The average maximum turbidity for pre-harvest condition was 84.3 (±17.5) NTU, which was not significantly different from the bag harvest average maximum (85.6 ± 66.7 NTU, $p$=0.92) or the post-harvest interval average maximum value (78.9 ± 16 NTU, $p$=0.436). This finding suggests that under the most extreme conditions observed in this research, there was no difference between natural disturbances and the bag harvest method. The average maximum turbidity for the pump-driven harvest was found to be higher than both the pre-harvest average maximum ($p$=0.018) and post-harvest average maximum ($p$=0.012). Interestingly, there was no statistically significant differences between the harvest methods ($p$=0.104), not a wholly unexpected result considering the large amount of variability observed during the replicates.

*Turbidity – Duration* While intensity is an important aspect of turbidity events, the duration of turbidity events is perhaps a more important characteristic (Day *et al*., 2013; Mercaldo-Allen and Goldberg, 2011; Valeila, 1995). We investigated this second component of turbidity by determining the time required to return to background condition. In all four replicates, the bag harvest method resulted in short term duration of turbidity with return intervals of 5 minutes or less while the pump-driven harvester return intervals were up to 9 minutes. These are very short intervals when viewed against natural turbidity events (Coen, 1995). During the replicates, several instances of natural events, which created prolonged elevated turbidity conditions, were observed. These observations suggest that duration of natural events can be significant and in some cases exceed turbidity associated with pump-driven harvesting (Drobeck and Johnston, 1982; Kaiser, 1998). Although quantitative comparisons to harvest turbidity duration are not appropriate here as the duration of harvest activities were controlled by experimental design, it should be noted that cessation of harvest activity results in a rapid return to background condition, while natural disturbances are not subject to such immediate changes (Figure 17).

To better place the effects of harvesting practices in context of natural conditions, several notable studies of pump-driven harvesting methods have found turbidity from these mechanical methods to be both spatially confined and temporally constrained when compared with natural events (Barnes *et al*., 1991; Black and Parry, 1999; Coen, 1995; Kaiser, 1998).The role of naturally induced turbidity events must not be overstated as they can be significant with respect to intensity as well as duration (Kyte and Chew, 1975). Monitoring of turbidity during these four replicates indicate the presence of natural processes in the area created episodic turbidity events with greater duration than those associated with pump-driven harvester activity. In this study, the pump-driven harvester did create higher turbidity than did natural events under most circumstances (88% of observations in Table 13); however, other relevant research suggests that natural events can induce extreme turbidity events several times greater in magnitude and duration (Black and Parry, 1999). This assertion is corroborated by observations during testing of a pump-driven harvester for harvesting bottom-planted hard clams *Mercenaria mercenaria* where natural events produced turbidity events of greater magnitude and duration than either the bag or pump-driven harvest methods (Sturmer *et al*., 2014) and several other studies conducted on mechanical shellfish harvesters (Drobeck and Johnston, 1982; Kyte and Chew, 1975; Tarnowski, 2006). Finally, the scale of disturbance from these harvest techniques should be considered with respect to natural disturbances. Harvesting of shellfish on aquaculture leases is not comparable spatially to regional disturbances (e.g., storms, tides, etc.), which may influence turbidity (Mercaldo-Allen and Goldberg, 2011; Tarnowski, 2006).

<u>Commercial-scale Harvest Trial</u> Operation of the pump-driven harvester occurred on an outgoing tide from 10:52-11:46am on 17 June 2014. Three sets of passes of the test plot, ranging from 10-13 minutes in duration, were made with the pump-driven harvester and replicated the effort required to harvest sunray venus clams in the prior field trials (see Appendix B). Between each set of passes, the pump was turned off for approximately 10 minutes simulating the time required to place harvested product into baskets and onto a boat. Tidal and wind data obtained from a nearby NOAA station are shown in Figure 18. During harvest, current velocity was 9.5cm/sec from north to south and water depth decreased from 2.7 to 2.2 feet. Turbidity during harvest and 24 hours pre- and post-harvest are presented in Figures 19-21. Average, minimum, and maximum turbidity values recorded over these time periods are summarized in Tables 14-16. In the 24 hours prior to harvest, average turbidity values were similar at all sonde locations, ranging from 23.4 (W-5) to 28.7 NTU (S-5). During harvest, the lowest turbidity average (13.8 NTU) was obtained at the sonde (SE-45) located the farthest from the test area, while the highest average (40.2 NTU) was recorded at the sonde (S-5) positioned immediately down current of the area. The average values during harvest were lower than those recorded in the previous 24 hours at all but two sondes (S-5 and W-5).

For the period 24 hours prior to the commercial-scale trial, the highest average turbidity observed in the sonde cluster within 5 feet of the harvest activity was 28.7 (±10.3) NTU compared to 40.2 (±19.1) NTU and 33.1 (±22.2) NTU for the harvest and 24 hour post-harvest periods, respectively. The harvest turbidity was found to be significantly higher than the pre-harvest condition ($p$=0.0017), however, there was no significant difference observed between the highest mean turbidity values of the harvest and post-harvest interval ($p$=0.059). Pre-harvest mean was found to be significantly lower than the post-harvest mean turbidity ($p<0.001$). Comparison of maximum values across the three sonde sets for the commercial- scale harvest trial indicated substantial natural turbidity events. At the 5-foot sonde cluster, 24 hour post-harvest had higher maximum values (155.2 NTU) in comparison to harvest (98.2 NTU) and 24 hour pre-harvest intervals (68.6 NTU).

At the sonde cluster 25 feet from the harvest activity, the highest mean turbidity in the 24 hours prior to harvest was 29.9 (±9.9) NTU, which was found to be statistically higher ($p<0.001$) than the harvest period mean (20.4 ± 11.6 NTU) and statistically lower ($p<0.001$) than the post-harvest period mean turbidity (32.0 ± 21.9 NTU). The harvest mean turbidity was also found to be statistically lower than the post-harvest mean ($p<0.001$). Similarly to the 5-foot sonde cluster, maximum values observed at this sonde cluster indicate greater magnitude of turbidity inducing events in the 24 hours pre-harvest (67.9 NTU) and 24 hours post-harvest (143.9 NTU) when compared to the harvest activity (60.3 NTU), suggesting natural events can exceed those of the harvest activity.

At the sonde cluster 45 feet from harvest site, during the 24 hour period prior to harvest, the highest mean observed was 28.4 (±10.2) NTU compared to 21.2 (±7.7) NTU for the harvest period and 31.1 (±19.6) NTU for the 24 hour period post-harvest. The pre-harvest mean was found to be significantly higher ($p<0.001$) than the harvest mean and significantly lower than the post-harvest. Likewise, the harvest mean was also significantly lower ($p<0.001$) than the post-harvest mean. Again, the sonde cluster at 45 feet indicated the maximum values observed during the pre- and post-harvest intervals (72.0 and 150.0 NTU, respectively) were higher than the actual harvest (46.4 NTU). Taken together, the three sets of sonde observations indicate that turbidity associated with harvest activity was only found to be statistically higher than the pre-harvest condition at the 5 foot sonde. At the 25 and 45 foot sondes, the pre-harvest mean was statistically greater, suggesting that the plume associated with the harvest activity was spatially constrained. Further, the harvest activity was observed to be significantly lower than the post-harvest mean in all cases suggesting that natural events can exceed the turbidity created by harvesting activity.

The maximum turbidity recorded during harvest was immediately down current of the harvesting activity at sonde S-5 (98.2 NTU). This was 32.3 NTU higher than the maximum value recorded at the same sonde during the 24 hours prior to harvest (65.9 NTU). With this exception, all maximum values at sondes during harvest (range, 16.9-60.3 NTU) were lower than those values 24 hours prior to harvest (range, 60.4-72.0 NTU) indicating natural variability had a wider and more intense effect on turbidity than the pump-driven harvester. Further, the maximum turbidity value recorded during the commercial-scale harvest was less than those recorded at the four sondes located five feet from harvest sites during the replicated experimental trials. Differences in turbidity intensity are most likely attributed to greater water depths encountered as the harvester suspends the same amount of sediment regardless of depth. Thus, the intensity of the turbidity pulse in deeper water was muted (Ruffin, 1998).

In the 24 hours post-harvest, average turbidity values, ranging from 26.4 to 32.0 NTU, increased at all sonde locations except for the south sonde (S-5, 33.1 NTU). The increase in turbidity levels coincided with two weather events (Figure 22). The first occurred from 7:54-8:06pm on June 17 with recorded wind speeds ranging from 10.3 to 12.1 knots out of the ENE. A lag in the turbidity response was observed as peak values, ranging from 61.6 to 84.9 NTU, occurred from 8:13-8:26pm. The second event occurred from 12:36-5:00am on June 18 with wind speeds averaging 12.8 knots and gusting to16.3 knots (recorded at 1:54am) out of the ESE, the wind direction which most influences the test area. Maximum turbidity recorded at all sondes, which ranged from 123 (S-25) to 155 NTU (S-5), occurred between 1:10-2:37am. The duration of the second weather event (approximately 4.5 hours) and associated wind effect on an incoming tide had a greater influence on turbidity values than the pump-driven harvester. Results from other studies examining the impacts of similar harvesting methods have shown that changes to subaqueous soils are variable and temporary, and that episodic weather events and other natural forces can produce effects to these soils and suspended sediments comparable to or greater than those associated with harvesting effects (Mercaldo-Allen and Goldberg, 2011; Tarnowski, 2006).

Turbidity values were examined at a finer temporal resolution (30 minutes pre-and post-harvest) to determine recovery to baseline conditions, defined as the average (±SD) of turbidity values recorded 30 minutes prior to harvest (Figures 23-25). Turbidity levels were most affected at the S-5 sonde location; however, values at harvest (max 86.3 NTU, first harvest set of passes; max 59.9 NTU, second set) returned to baseline levels of 19.1 (±2.6) NTU within 3 minutes after the first set and immediately after the second set (Figure 22). Turbidity levels (max 98.2 NTU) at the S-5 sonde location took longer (7 minutes) to dissipate after the third harvest set due to tidal change. At the S-25 sonde location, turbidity (max values per harvest set ranged from 24.1 to 60.3 NTU) returned to baseline levels of 13.1 (±1.4) NTU within 2 to 10 minutes (Figure 23). At the S-45 sonde location, turbidity returned to background levels of 17.8 (±0.9) NTU within 6 minutes after the first harvest set (Figure 24). Little to no change in turbidity was apparent during or after the second set (max 24.6 NTU) as values returned to baseline levels during harvest, while recovery of turbidity levels (max 21.9 NTU) after the third set was 8 minutes. These data indicate that turbidity changes caused by the use of a small, pump-driven harvester are variable and short-lived pulse events that dissipate rapidly.

Soil Characteristics Properties of soils sampled prior to planting sunray venus clams under the bottom nets and in bottom bags are presented in Table 17. Sand (means of 96.7-97.2 percent), fines (2.8-3.2 percent), and organic matter (1.0-1.2 percent) contents were statistically similar ($p>0.05$), indicating the soils within the planting area were relatively uniform at that time. Particle size and organic matter (OM) content of soils sampled prior to planting and at the reference (unfarmed) sites at harvest (week 0) are presented in Table 18. Although significant differences ($p=0.045$) occurred in the sand and fine contents of these soils between pre-planting and harvest, the variation was minimal as sand increased from 96.7 to 97.7 percent and fines decreased from 3.0 to 2.3 percent over a 11-13 month period. Organic matter content of soils at plant (1.1 percent) and harvest (0.8 percent) was similar ($p=0.07$).

Differences in soil properties between culture/harvest methods and reference sites at harvest and four and eight weeks post-harvest are presented in Table 19 and illustrated in Figures 26 and 27. These methods minimally affected soil properties when compared to the reference (unfarmed) soils. At harvest (week 0), soil properties at the bottom plant (98.0 percent sand, 1.6 percent silt, 0.4 percent clay, 0.7 percent OM) and bottom bag (97.4 percent sand, 1.9 percent silt, 0.4 percent clay, 1.2 percent OM) culture sites were similar ($p>0.05$) to the reference sites (97.7 percent sand, 1.9 percent silt, 0.4 percent clay, 0.8 percent OM). This was observed again at four weeks post-harvest, as soil properties at the bottom plant (95.5 percent sand, 3.2 percent silt, 1.2 percent clay, 0.7 percent OM) and bottom bag (96.1 percent sand, 3.2 percent silt, 0.7 percent clay, 0.6 percent OM) culture sites were similar ($p$>0.05) to the reference sites (95.1 percent sand, 3.9 percent silt, 0.9 percent clay, 1.0 percent OM). However, after eight weeks, sand (96.1 percent) and silt (2.6 percent) contents at the bottom bag sites were significantly higher than at the bottom plant (93.8 percent sand, 4.9 percent silt, $p$=0.02) and reference (93.5 percent sand, 5.1 percent silt, $p$=0.002) sites. Further, organic matter content (1.4 percent) was greater ($p$=0.04) at the bottom bag sites than bottom plant sites (0.6 percent), but similar to the reference sites (0.8 percent). Changes observed post-harvest were most likely due to normal variations in soil properties. The clay fraction (0.4-1.3 percent) of soils did not differ ($p$>0.05) between treatment sites at any of the sample periods.

Differences in soil properties within culture methods and reference sites over time are also illustrated in Figures 26 and 27. Sand content significantly decreased from week 0 to week 4 at the bottom plant (99.0 to 95.5 percent, $p$=0.001) and reference (97.7 to 95.1 percent, $p$=0.001) sites, and from week 0 to week 8 at the bottom plant (99.0 to 93.7 percent, $p$=0.001) and reference (97.7 to 93.5 percent, $p$=0.001) sites (Figure 26). Inversely, silt values increased ($p$=0.0008) at bottom plant sites from week 0 to week 4 (1.6 to 3.2 percent), week 0 to week 8 (1.6 to 4.8 percent), and from week 4 to week 8 (3.2 to 4.9 percent) (Figure 26). Silt also increased ($p$=0.0007) from week 0 to week 4 (1.8 to 3.9 percent) and week 0 to week 8 (1.8 to 5.1 percent) at reference sites. Clay content and organic matter were similar ($p$>0.05) for all treatments and weeks (Figure 27).

In a review of the effects of mechanical dredging, shellfish harvesting activities were considered negligible compared to environmental variation (Coen, 1995). Effects of hydraulic dredge harvesting, such as changes in soil particle size and track depth extent/recovery, were considered site-specific and dependent on soil grain size and type, hydrologic conditions, bioturbation, and climatic events (Barnes *et al*., 1991). In a study that examined the use of a hydraulic escalator dredge to harvest soft shell clams in Chesapeake Bay, Pfitzenmeyer (1972) stated that operation in areas with medium to fine grain sands at least 12 inches in depth resulted in no major changes to soil structure. He also commented that although soils were similar in structure, they were "softer" in dredged areas at least one year after dredging. In this study, soil particle size distribution differed at the reference (unfarmed) sites from plant to harvest, and at bottom plant and reference sites post-harvest. Although a reduction of sand content and an increase in fines (silt) content occurred at both of these sites after harvest, these changes were minimal and did not alter the textural classification of soils as "sand" as defined by USDA (Soil Survey Division Staff, 1993). Interestingly, soils at the bottom bag sites did not experience significant changes within any soil property. This may be due to compaction that tends to occur under bottom bags, leaving soils not as susceptible to normal tidal and weather events as the reference and bottom plant sites. Similarly, geoduck farming sites had firmer substrates than unfarmed sites in the Pacific Northwest (Fisher *et al*., 2008). Although soils differed within culture/harvest methods and reference sites in this study, it was not until eight weeks post-harvest that differences between methods occurred, suggesting soil particle size variation was most likely due to normal environmental changes.

Harvest Track Depth and Recovery The extent of the harvest tracks for the bottom plant and bottom bag sites at weeks 0, 4 and 8 post-harvest is presented in Table 20 and illustrated in Figure 28. The average depth of tracks (-3.75 cm) created by the pump-driven harvester was significantly deeper ($p$=0.003) immediately after harvest (week 0) than at the bottom bag harvest sites (+3.70 cm). Although tracks at the bottom plant sites filled in over time, soil elevations (-1.76 cm, week 4;-1.59 cm, week 8) were significantly lower ($p$=0.02, week 4; $p$=0.01, week 8) than at the bottom bag sites (0.25 cm, week 4; -0.93 cm, week 8). The depth of the harvest tracks at the bottom plant sites significantly diminished ($p$=0.01) from week 0 to week 2 ($\Delta$=1.94 cm), but leveled out ($\Delta$=0.17 cm) between weeks 4 and 8. Total infill over the eight weeks at these sites averaged 2.11 cm. Soil elevations significantly decreased ($p$=0.0004) at the bottom bag sites from week 0 to 4 ($\Delta$=-3.50 cm) and from week 4 to 8 ($\Delta$=-1.18 cm). Average soil loss over time at the bottom bag sites was 4.68 cm.

Soil recovery trends at the bottom bag and bottom plant sites differed significantly ($p$<0.05) for each sample period. At harvest, bottom bag sites exhibited a higher soil elevation (3.70 cm) than bottom plant sites (-3.75 cm). The mounding created by bottom bag culture (measured at harvest) was similar to that attributed to the presence of netting in a study that examined ecological effects of intertidal manila clam cultivation (Spencer *et al*., 1997). Netting, and not clams, increased the sedimentation rate and retention of fines and organic matter, which raised soil elevation by ~10 cm. In this study, we measured soil elevation after harvesting not during cultivation. Due to the dynamics described by Spencer *et al*. (1997) and the manner in which the bottom bags were harvested ("washing" sediments from bags in place), soil elevation at bag sites should be higher than at bottom plant sites. By the same measure, mounding under bottom plants should occur as well. If soil elevation was measured after the removal of the nets covering the bottom planted sunray venus clams, and not after using the harvester, this mounding effect may also have been evident. This was substantiated by observations from the harvester operator, who could detect increases in soil elevation changes near the center of the bottom plants.

The average depth of tracks created by the pump-driven harvester was relatively small (-3.75 cm). Given that the harvester "digs" into the soil ~6" (15 cm) to retrieve sunray venus clams, infill appeared to occur during and immediately after harvest. This was most likely due to the harvester design and soil dynamics. The harvester shunts material to a removable wire-mesh basket which collects the clams and allows soil particles to pass through. Because of the high sand content of the soils (average >93%), heavier sand particles were re-suspended for short periods of time, falling within or near the tracks. Similarly, Godcharles (1971) reported that tracks created by hydraulic dredging conducted at Seahorse Reef near Cedar Key filled rapidly to a depth of 18 inches with soupy sand from adjacent soils almost immediately after harvesting. Only a two-inch ridge on either side of the dredge path differentiated it from unaltered soils. Although soil elevations did not return to pre-harvest levels, the average track depth (-1.6 cm) at the bottom plant sites was minimal after 8 weeks post-harvest, whereas the average track depth at the bottom bag sites was -0.9 cm, only a 0.7 cm difference between the harvest sites. This variation could certainly be due to normal variations in bottom topography. In another study, tracks created by hydraulic dredging of sand-bottomed, subtidal waters in Lamash Harbor, Scotland resulted in an average track depth of 13.9 cm, which was reduced to 2.9 cm within 100 days (Hauton and Paterson, 2003). Depths of these tracks diminished from approximately 5.0 to 2.9 cm, a difference of 2.1 cm, in less than 40 days (from day 60 to day 100). Similarly, average total infill in this study was 2.11 cm after eight weeks at the harvested bottom plant sites. Infill at these sites and the concurrent loss of soil from the bottom bag sites reflect recovery of soils over time to levels similar to reference conditions.

*Suitability of Leases for Sunray Venus Clam Production*

Soil kits were mailed to growers to sample 25 lease sites; at each of the sites, the soils were to be sampled in triplicate. Nine growers returned 57 soil samples collected at 18 lease sites in five counties. A soil test report (*Subaqueous Soil Acceptability for Sunray Venus Culture:Test Results*) was developed and provided to each participating grower with results and information on how they relate to acceptability of sunray venus clam culture (Appendix C). In a prior Florida Sea Grant-funded project, growth experiments with sunray venus in soils ranging from 80 to 100% sand and 0 to 9% organic matter indicated that soils with >85% sand, <10% clay, and <5% organic matter were suited for culturing these clams (Ellis and Osborne, 2011). Mortality and shell deformities associated with bottom sediments were minimized above 85% sand; growth increased with increased sand content. These soil types generally fall within the USDA textural class of "sand." Results from another Florida Sea Grant project conducted at commercial leases with variable soil characteristics indicated that all other textural classes would have a lower suitability for culturing sunray venus clams. Results of soil analyses in this study were plotted on an expanded view of the soil textural triangle, which was color-coded, representing where samples fell (see Appendix B). For example, the green-shaded area of the triangle represented recommended soil conditions for sunray venus clams, whereas the yellow-shaded zone represented conditions in which shell deformities begin to increase and are marginally recommended. Unshaded areas were not recommended for sunray venus clam culture. Soil particle size distribution varied by lease location with sand content ranging from 79 to 98%, silt content from 0 to 9%, and clay content from 0 to 14%. Organic matter values ranged from 0.5-6.7% at these sites. Seventeen of the lease sites tested had soil properties recommended for sunray venus culture. Characterization of soil types and chemistry may aid in determining compatibility of existing shellfish aquaculture leases or in siting future leases for this bivalve.

## Summary

To advance the production of a promising new aquaculture species, the sunray venus clam *Macrocallista nimbosa*, alternative farming technology was evaluated. Bottom planting under cover nets, a method used in other states for hard clam culture, may be more suitable for the sunray venus clam as opposed to bottom bags, which is the method typically used by Florida growers. In this study, an 80 percent increase in production was obtained using bottom plants versus bottom bags (Table 2). Further, the culture period to reach potential market size (~50 mm shell length) can be reduced by 15-25 percent using this method, which lessens the risks associated with mortalities resulting in higher crop survival. Product quality of sunray venus clams harvested from bottom plants was not compromised as shell deformities, shell breakage, meat grittiness after purging, and shelf life in refrigerated storage (Tables 3-5) did not differ or was improved when compared to sunray venus clams cultured and harvested in bottom bags. Development of alternative culture species represents an important gain over the present reliance of a single species crop for the Florida shellfish aquaculture industry.

To address the need for diversification and obtain full adoption of this alternative culture species by industry, we evaluated the use of a small pump-driven device to harvest bottom-planted sunray venus clams. Reliance on manual methods, such as a hand rake, for harvest would not be commercially viable. Although clam farming in Florida occurs on designated shellfish aquaculture lease areas, devoid of seagrasses and other sensitive bottom habitats, there is warranted concern surrounding the use of mechanical harvesting techniques that are untested as to the potential environmental impact they may incur. While pump-driven harvesters are used extensively in other states, it was important to test them in Florida in actual lease conditions to determine extent and duration of potential environmental impacts (Giesen *et al*., 1990; Hemminga and Duarte, 2000; Wetzel, 2001). Therefore, this research was conducted to provide science-based information on the potential impact of using pump-driven harvesters on shellfish aquaculture leases. The effects on water quality and soil physiochemical properties from harvesting bottom-planted sunray venus clams via this method were examined and compared to harvesting sunray venus clams in bottom bags.

The results of the soil investigation suggested that little effect was observed in the surface soils with respect to harvest induced change in particle size distribution (PSD). Subaqueous soils were sampled prior to planting, then repeatedly post-harvest at 0, 2, and 4 weeks to evaluate soil properties and changes in soil elevations. Soil particle size and organic matter content did not differ between harvest or reference (unfarmed) sites (Figures 26 and 27). Furthermore, consistent changes among treatments over the eight-week period suggested that natural processes were far more active in sorting soil particle size than were the methods of harvest tested here. Hence, the observation that all soils, including those of the reference (untreated) experienced PSD changes similar in magnitude and directionality overshadows any effect from the harvesting techniques (Table 19). Ostensibly, these changes are caused by environmental factors other than the use of the pump-driven harvester, such as tidal flux, wind events, and natural currents. This observation is not unique to this study as natural disturbances have been noted to alter surface soil attributes rapidly on aquaculture leases in Florida (Ellis, 2006; Sturmer *et al*., 2014; White *et al*., 2012). Tracks were apparent after harvesting due to the displacement of soils, a common observation made among different harvesting techniques (Mercaldo-Allen and Goldberg, 2011). Although harvest tracks created by the pump-driven harvester were significantly different than those created by harvesting bags, the track depths were shallow (-3.75cm post-harvest) and continued to recover over the monitoring period (-1.59cm after 8 weeks) (Table 20). In prior work, we reported that recovery of sandy soils would benefit from a fallow period of one to two months at commercial leases where bottom bag culture was used (White *et al*., 2012). This does not appear to be the case when using the pump-driven harvester, as soil PSD mirrored that of bag and reference sites immediately after harvest. It is important to note that natural variability in soil dynamics and transport was greater than harvesting effects, and thus is strongly indicated as the determining force in PSD.

Changes to water quality in the form of temperature, dissolved oxygen, salinity, and turbidity were all monitored during these field trials (Tables 6-12). Water quality parameters were measured continuously 48 hours prior to harvest, during harvest, and 48 hours post-harvest. Values for water temperature, salinity, and dissolved oxygen did not differ during harvests of the two culture methods. Only turbidity showed any noticeable difference with respect to background condition. Turbidity is arguably the water quality parameter of greatest interest with respect to the pump-driven harvester use. On average, turbidity appeared higher during the harvest of bottom plants (maximum value of 248 NTU) and bags (maximum value of 186 NTU) than the pre-harvest and post-harvest intervals; however, statistical differences were only noted in two replicates (Figure 12). Similarly, there was no significant difference observed in any replicate between the mean turbidity values observed during the use of the pump-driven harvester or the bag harvest. Impacts of harvesting activities to the water column were short-term as turbidity values returned to background levels within nine minutes.

When evaluating the observations of the "commercial-scale" harvest trial, the mean turbidity associated with the harvest activity was significantly lower than the pre-harvest mean at all but the closest sonde (5ft) and significantly lower than the post-harvest condition at all sonde distances suggesting natural events can exceed turbidity produced from harvest activity. With respect to the experimental field replicates, the commercial trial had lower mean turbidity (Table 14-16) than similar activities during the field replicates. This finding is attributed to differences in environmental conditions and we contend that turbidity effects were diminished due to higher water levels (2.2-2.7ft) during the commercial harvest versus <1.0ft during the field replicates. Higher water levels and tidal height suggest more dispersion of turbidity plumes, which, in turn, lower the observed intensity of the turbidity events. Based on these observations, maximizing water depths, whenever feasible, and avoiding tidal peaks (e.g., spring or neap lows) may mitigate turbidity events.

We conclude that:

1) For both bag and pump-driven harvest methods, turbidity was the only water quality parameter observed to change during harvesting of sunray venus clams.
2) Although the pump-driven harvester had the highest observed turbidity, there was no statistically significant difference observed between the maximum mean turbidity from bag harvest versus the pump-driven harvester in all field replicates.
3) Turbidity decreased rapidly following cessation of the harvest activity. Turbidity conditions returned to background levels within 5-9 minutes post-harvest using the pump-driven harvester.
4) High variability in reference (pre and post) water quality suggest elevated turbidity conditions are common within the study area and that natural events can induce turbidity conditions similar to harvester activity in magnitude and often much greater in terms of duration.
5) A commercial-scale harvest trial captured the immense variability in background or natural turbidity inducing events. The magnitude of these events can be significantly higher than potential impacts of the harvest activity itself.
6) The pulse disturbance created by harvesting activities, when viewed within the context of natural and normal disturbances observed in shallow coastal environments, are relatively inconsequential with respect to the production of turbidity.
7) Therefore, we accept the hypothesis that effects of harvesting bottom-planted sunray venus clams with a pump-driven device are similar to those associated with harvesting bottom bags.

Although harvesting of infaunal bivalve species affects all soils and their constituents in some way, most effects are short-lived and not considered to have deleterious effects when compared to natural environmental variation. Potential effects can vary, but are limited by the process itself (immediate return of soil to the bottom), and are largely dependent on site-specific parameters, such as soil grain size, type, and hydrological conditions (Barnes *et al*., 1991). Also, the manner in which harvesting is conducted determines effects and their extent. The quantification of these effects has only recently been compiled into several extensive literature reviews (Mercaldo-Allen and Goldberg, 2011; Rheault, 2008). Overall, our findings consistently support results found in the numerous published studies in these reviews, which conclude that the physical, biological, and chemical effects of mechanical shellfish harvesters are generally short-lived with the rate of recovery varying among studies. Recent research conducted by scientists at the NOAA Fisheries, Northeast Fisheries Science Center in Milford, Connecticut corroborates our work (Goldberg *et al*., 2012; Goldberg *et al*., 2014). Their findings, as ours, show that short-term effects of mechanical harvesters are minimal, with no long-term, chronic effect, even under worst-case scenarios. As summarized by Coen (1995) in his review of potential impacts of mechanical harvesting in South Carolina, our observed effects were often indistinguishable from ambient levels or natural coastal estuarine variability. The most obvious effect (sediment plume) ceased when harvesting was completed, but natural events are continuous.

*Considerations Regarding Mechanical Harvesting Cultured Shellfish on Aquaculture Leases*

The goal of this study was to provide science-based information to address statutory and/or regulatory barriers that serve as constraints in establishing the sunray venus clam and other potential aquaculture species as feasible complements to hard clams. The following discussion will allow environmentalists, resource managers, and others to differentiate the impacts of using a pump-driven device to harvest cultured shellfish on aquaculture leases from those associated with dredge harvesting of natural populations, which support shellfisheries. The two practices differ greatly in the frequency and scale of harvest activity with important ramifications on the degree of impact. Dredges used to harvest shellfish are designed to capture shellfish, leaving sediment behind and should not be confused with channel or navigational dredging, which is used to deepen waterways by removing sediments. There are other considerations pertaining to shellfish aquaculture activities that ameliorate potential impacts of harvesting. Much of the following is excerpted from a review “Environmental Impacts Related to Mechanical Harvest of Cultured Shellfish” by Stokesbury *et al*. (2011).

- Shellfish farms in Florida operate in shallow coastal or estuarine environments and are exposed to natural disturbances from terrestrial and marine sources. For example, heavy rainfall from hundreds of miles inland can result in pronounced drops in salinities and water clarity. Wave action from frontal systems or storms resuspends sediments turning entire waters brown with turbidity. These high-energy estuarine environments are adapted to frequent disturbances.
- Submerged lands proposed for aquaculture lease sites must undergo a site inspection and comprehensive resource survey by the FDACS Division of Aquaculture and Florida Department of Environmental Protection staff to evaluate environmental and ecological parameters that may be affected by shellfish culture activities (Chapter 597.003, F.S.). Shellfish farms are approved in areas which minimize or eliminate adverse impacts to fish and wildlife habitat. Leased bottoms do not contain seagrasses and buffer zones may be established to minimize threats to adjacent seagrass communities.

- Shellfish farmers in Florida are certified with the FDACS Division of Aquaculture and must follow best management practices on their farms (Chapter 5L-3, F.A.C.) Authorized activities include planting and harvesting of shellfish. Farmers are also allowed to wash harvested shellfish on their leases (Chapter 5L-1, F.A.C.). Most farmers use the same size pump for this post-harvest activity as was used in this study. This approved activity also results in a short-lived sediment plume.
- Shellfish farmers know exactly where their crops are planted on their leased bottoms and when they are ready to be harvested. Since farmers know the spatial distribution or density of their crops, intensive harvesting efforts are not necessitated. Further, on shellfish farms harvesting efforts are of short duration as the density is much higher than in wild populations. For example in this study, we proposed that 10,000 sunray venus clams could be harvested from a 300 $ft^2$ bottom plant, which represents <1 percent of an acre. The time to harvest this amount with a small pump-driven device would be less than an hour.
- Shellfish farmers need to allow their crops to grow undisturbed for many months, in some cases up to two years, before harvesting. At any given time, a farmer will harvest only a small portion of the farm while the rest is left to grow. As a result, cultured bottom may be more diverse and productive because of high shellfish biomass.
- One of the impacts attributed to dredge harvesting is the flattening of vertical structure and reducing habitat complexity (Bradstock and Gordon, 1983). Most shellfish leases are devoid of vertical structure. In clam aquaculture farms, there is typically little structure to begin with, the disturbance of harvest activity is short term, and recovery is rapid.
- The ecological communities associated with shellfish culture may differ somewhat from the initial benthic fauna, just as occurs in traditional agriculture when fields are cleared for replanting (Watling, 2005). Although frequent culture activities (planting, harvesting) can prevent benthic succession to climax communities (Wilber *et al*., 2008), the intention of both terrestrial and shellfish farming is to cultivate a particular crop rather than to allow the site to reach a climax community. Further, species that live in these environments are well adapted to periodic disturbances from storm events and wave action.
- Shellfish farmers in Florida reseed their crops continuously. By planting seed clams, not only is physical structure restored, but habitat productivity is enhanced and resource sustainability is promoted.

This study was initiated upon on a request from the Florida Clam Industry Task Force in 2012 that research on alternative harvesting methods, which would minimize impacts to natural resources and potentially improve clam production, be conducted. Funding for this work was provided through FDACS; a proposal submitted to the Aquaculture Review Council ranked first in priority for inclusion in the Department's 2013-14 budget. The science provided by this research can be used by the FDACS Division of Aquaculture and other agencies in consideration of legislative or regulatory changes to allow for the use of small pump-driven harvesters on shellfish aquaculture leases. Recently, the USDA Farm Service Agency recognized the use of alternative farming techniques and shellfish culture species by Florida clam growers. Coverage for bottom plant methods and sunray venus clams in selected counties is now available through their Noninsured Crop Disaster Assistance Program, or NAP (Paul Zajicek, pers. comm.).

Based on our research findings, we recommend revised interpretation or minor changes in current laws to allow for this alternative harvesting activity. Over the past twenty years, a prohibition on using mechanical harvesting devices to harvest hard clams from aquaculture leases has been included in aquaculture lease agreements as a special lease condition. If Chapters 253 and 597, F.S. were to be amended to include the use of small, pump-driven harvesters, special lease conditions could provide for special terms and requirements in their operation. The Aquaculture Best Management Practices (Chapter 5L-3, F.A.C.) include a provision in Section X, B stating that "Mechanical harvesting is prohibited on aquaculture grow-out areas unless specified in the lease agreement or development plan for culture operations." Best management practices could also be developed for operation of pump-driven harvesting devices on shellfish aquaculture leases to allow for increased commercial production while preserving environmental integrity.

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**Tables and Figures**

**Table 1.** Averages and standard deviations (±SD) of sunray venus clams (*n*=50 clams/replicate) at plant.

| Replicate | Shell Width (mm) | Shell Length (mm) | Shell Height (mm) | Total Weight (mm) |
|---|---|---|---|---|
| **1** | 9.0 ± 1.5 | 26.9 ± 4.6 | 16.0 ± 2.6 | 2.7 ± 1.2 |
| **2** | 8.7 ± 1.5 | 25.3 ± 4.4 | 15.2 ± 2.4 | 2.3 ± 1.1 |
| **3** | 8.2 ± 1.4 | 24.0 ± 4.3 | 14.5 ± 2.5 | 2.1 ± 1.1 |
| **4** | 8.7 ± 1.4 | 25.3 ± 4.0 | 15.2 ± 2.1 | 2.4 ± 1.0 |
| **Overall Average** | 8.6 ± 0.4 | 25.4 ± 1.2 | 15.2 ± 0.6 | 2.4 ± 0.3 |

**Table 2.** Average production characteristics and standard deviations (±SD) of sunray venus clams cultured under bottom nets and in bottom bags (*n*=4 culture method replicates) at harvest. Data were analyzed by t-tests.

| Culture Method | Survival (%) | Shell Length (mm) | Shell Width (mm) | Total Weight (mm) | Meat Weight (mm) | Yield ($lb/ft^2$) |
|---|---|---|---|---|---|---|
| **Bottom Plant** | 47.4 ± 7.8 | 61.9 ± 1.1 | 21.2 ± 0.5 | 29.9 ± 2.2. | 8.3 ± 1.4 | 1.8 ± 0.4 |
| **Bottom Bags** | 48.4 ± 7.9 | 48.1 ± 1.4 | 18.6 ± 0.6 | 17.3 ± 1.3 | 4.7 ± 0.5 | 1.0 ± 0.2 |
| *t* value | 0.19 | -15.03 | -6.89 | -9.83 | -5.06 | -3.51 |
| *p* value | 0.8586 | <0.0001 | 0.0005 | <0.0001 | 0.0023 | 0.0126 |

**Table 3.** Average ratings, where a value of 0 = "not gritty" and a value of 4 = "very gritty," and standard deviations (±SD) for grittiness found in sunray venus clams harvested from bottom plants and bottom bags and purged for 24 hours in October 2013. Data were analyzed by t-tests.

| Culture Method | Not Purged (Rating) | Purged 24-hours (Rating) |
|---|---|---|
| **Bottom Plant** | 1.48 ± 0.73 | 0.61 ± 0.38 |
| **Bottom Bags** | 0.94 ± 0.71 | 0.22 ± 0.20 |
| *t* value | 1.69 | 2.82 |
| *p* value | 0.1088 | 0.0114 |

**Table 4.** Average ratings, where a value of 0 = "not gritty" and a value of 4 = "very gritty," and standard deviations (±SD) for grittiness found in sunray venus clams harvested from bottom plants and bottom bags and purged for 24 and 48 hours in November 2013. Data were analyzed by t-tests.

| Culture Method | Not Purged (Rating) | Purged 24-hours (Rating) | Purged 48-hours (Rating) |
|---|---|---|---|
| **Bottom Plant** | 1.69 ± 1.04 | 0.51 ± 0.44 | 0.27 ± 0.27 |
| **Bottom Bags** | 1.26 ± 0.93 | 0.40 ± 0.53 | 0.31 ± 0.36 |
| *t* value | 0.97 | 0.49 | -0.27 |
| *p* value | 0.3450 | 0.6338 | 0.7927 |

**Table 5.** Averages and standard deviations (±SD) for gaping of sunray venus clams during 10 days in refrigerated storage. Sunray venus clams were harvested from bottom plant and bottom bag culture methods in October 2013 (field replicate 1), when ambient water temperature at harvest was 74°F, and in December 2013 (field replicate 3), when ambient water temperature at harvest was 59°F. Data were analyzed by repeated measures ANOVA and least significant difference tests.

| Culture Method | Replicate | Gaping (%) | | | | |
|---|---|---|---|---|---|---|
| | | Day 2 | Day 4 | Day 6 | Day 8 | Day 10 |
| **Bottom Plant** | 1 | 45.6 ± 7.8 | 25.4 ± 9.2 | 37.2 ± 7.1 | 30.9 ± 3.4 | 35.4 ± 2.6 |
| **Bottom Bags** | 1 | 35.1 ± 6.7 | 15.6 ± 9.4 | 27.1 ± 6.8 | 17.8 ± 9.0 | 19.6 ± 2.1 |
| *t value* | | 1.77 | 1.30 | 1.77 | 2.35 | 8.18 |
| *p value* | | 0.1519 | 0.2640 | 0.1514 | 0.0789 | 0.0012 |
| **Bottom Plant** | 3 | 5.0 ± 1.0 | 7.4 ± 2.3 | 0 ± 0 | 8.0 ± 5.2 | 8.1 ± 7.1 |
| **Bottom Bags** | 3 | 3.0 ± 2.0 | 9.0 ± 1.1 | 0.7 ± 0.6 | 6.7 ± 4.2 | 7.0 ± 3.0 |
| *t value* | | 1.55 | -1.15 | -2.00 | 0.35 | 0.23 |
| *p value* | | 0.1951 | 0.3127 | 0.1161 | 0.7437 | 0.8281 |

**Table 6.** Averages and standard deviations (±SD) of water temperatures for all field replicates measured at sondes located adjacent to the bottom plant (BP) and bottom bag (BB) culture sites during harvest and 30 minutes pre- and post-harvest. Sonde position is noted as direction, culture method, and distance from the adjacent culture site (e.g., N-BP-5). The sonde located between culture sites is designated as MID. Sondes were also positioned 25 feet down current from each culture site. These sondes are designated as BP-25 and BB-25 as their position (either north or south) was dependent on whether harvesting occurred on an incoming or outgoing tide.

| Sonde Location | Water Temperature (°F) | | | |
|---|---|---|---|---|
| | 30 min Pre-Harvest (Avg ±SD) | Bottom Bag Harvest (Avg ±SD) | Bottom Plant Harvest (Avg ±SD) | 30 min Post-Harvest (Avg ±SD) |
| N-BP-5 | 64.2 ±9.6 | 64.4 ±9.2 | 64.8 ±8.8 | 65.1 ±8.5 |
| S-BP-5 | 64.2 ±8.6 | 64.4 ±8.2 | 64.8 ±7.8 | 65.1 ±7.6 |
| W-BP-5 | 64.6 ±8.7 | 64.8 ±8.7 | 65.2 ±8.2 | 65.5 ±8.0 |
| N-BB-5 | 63.8 ±9.9 | 64.0 ±9.6 | 64.4 ±9.1 | 64.7 ±8.8 |
| S-BB-5 | 63.9 ±9.6 | 64.0 ±9.4 | 64.3 ±9.0 | 64.6 ±8.8 |
| E-BB-5 | 63.1 ±7.3 | 63.2 ±7.2 | 63.5 ±6.7 | 63.8 ±6.5 |
| MID | 64.8 ±8.7 | 64.9 ±8.6 | 65.2 ±8.1 | 65.5 ±7.9 |
| BP-25 | 64.8 ±8.9 | 65.0 ±8.6 | 65.4 ±8.1 | 65.6 ±7.9 |
| BB-25 | 64.4 ±10.7 | 64.6 ±10.4 | 65.1 ±9.8 | 65.4 ±9.6 |

**Table 7.** Averages and standard deviations (±SD) of salinities for all field replicates measured at sondes located adjacent to the bottom plant (BP) and bottom bag (BB) culture sites during harvest and 30 minutes pre- and post-harvest. Sonde position is noted as direction, culture method, and distance from the adjacent culture site (e.g., N-BP-5). The sonde located between culture sites is designated as MID. Sondes were also positioned 25 feet down current from each culture site. These sondes are designated as BP-25 and BB-25 as their position (either north or south) was dependent on whether harvesting occurred on an incoming or outgoing tide.

| Sonde Location | Salinity (ppt) | | | |
|---|---|---|---|---|
| | **30 min Pre-Harvest (Avg ±SD)** | **Bottom Bag Harvest (Avg ±SD)** | **Bottom Plant Harvest (Avg ±SD)** | **30 min Post-Harvest (Avg ±SD)** |
| **N-BP-5** | 27.5 ±1.1 | 27.5 ±1.0 | 27.4 ±1.0 | 27.5 ±1.0 |
| **S-BP-5** | 27.6 ±0.5 | 27.5 ±0.5 | 27.6 ±0.5 | 27.7 ±0.5 |
| **W-BP-5** | 27.3 ±0.4 | 27.3 ±0.3 | 27.3 ±0.3 | 27.3 ±0.3 |
| **N-BB-5** | 27.5 ±0.6 | 27.5 ±0.6 | 27.5 ±0.6 | 27.5 ±0.5 |
| **S-BB-5** | 27.5 ±0.7 | 27.4 ±0.7 | 27.4 ±0.7 | 27.5 ±0.7 |
| **E-BB-5** | 27.3 ±0.5 | 27.3 ±0.4 | 27.3 ±0.3 | 27.3 ±0.3 |
| **MID** | 27.2 ±0.5 | 27.1 ±0.4 | 27.1 ±0.4 | 27.2 ±0.3 |
| **BP-25** | 26.5 ±1.8 | 25.9 ±3.0 | 27.1 ±0.2 | 27.2 ±0.3 |
| **BB-25** | 27.6 ±0.8 | 27.6 ±0.7 | 27.6 ±0.7 | 27.6 ±0.7 |

**Table 8.** Averages and standard deviations (±SD) of dissolved oxygen values for all field replicates measured at sondes located adjacent to the bottom plant (BP) and bottom bag (BB) culture sites during harvest and 30 minutes pre- and post-harvest. Sonde position is noted as direction, culture method, and distance from the adjacent culture site (e.g., N-BP-5). The sonde located between culture sites is designated as MID. Sondes were also positioned 25 feet down current from each culture site. These sondes are designated as BP-25 and BB-25 as their position (either north or south) was dependent on whether harvesting occurred on an incoming or outgoing tide.

| Sonde Location | Dissolved Oxygen (mg $L^{-1}$) | | | |
|---|---|---|---|---|
| | 30 min Pre-Harvest (Avg ±SD) | Bottom Bag Harvest (Avg ±SD) | Bottom Plant Harvest (Avg ±SD) | 30 min Post-Harvest (Avg ±SD) |
| **N-BP-5** | 6.8 ±1.7 | 7.0 ±1.4 | 7.1 ±1.3 | 7.1 ±1.2 |
| **S-BP-5** | 6.3 ±2.1 | 6.3 ±2.1 | 6.6 ±1.6 | 6.7 ±1.6 |
| **W-BP-5** | 5.4 ±1.4 | 5.4 ±1.3 | 5.5 ±1.3 | 5.5 ±1.1 |
| **N-BB-5** | 7.4 ±1.3 | 7.3 ±1.2 | 7.4 ±1.2 | 7.4 ±1.1 |
| **S-BB-5** | 6.5 ±0.6 | 6.9 ±0.8 | 6.9 ±0.7 | 7.0 ±0.6 |
| **E-BB-5** | 7.1 ±2.1 | 6.8 ±1.6 | 6.8 ±1.6 | 6.9 ±1.6 |
| **MID** | 5.5 ±3.0 | 5.5 ±2.9 | 5.6 ±2.9 | 5.7 ±2.9 |
| **BP-25** | 6.0 ±1.2 | 6.1 ±1.0 | 6.1 ±0.9 | 6.2 ±0.7 |
| **BB-25** | 7.8 ±2.4 | 7.6 ±2.3 | 7.5 ±2.1 | 7.4 ±1.8 |

**Table 9.** Turbidity (NTU) values for replicate harvest #1 from 30 minutes pre-harvest to 30 minutes post-harvest at sondes located adjacent to the bottom plant (BP) and bottom bag (BB) culture sites. Harvest time for sunray venus clams in bottom bags was 9 minutes, while bottom-planted sunray venus clams required 39 minutes to harvest using the pump-driven device. Sonde position is noted as direction, culture method, and distance from the adjacent culture site (e.g., N-BP-5). The sonde located between culture sites is designated as MID. Sondes were also positioned 25 feet down current from each culture site. These sondes are designated as S-BP-25 and S-BB-25 as their position was dependent on the outgoing tide.

| Sonde Location | Turbidity (NTU) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 30 min Pre-Harvest | | | Bottom Bag Harvest | | | Bottom Plant Harvest | | | 30 min Post-Harvest | | |
| | Avg ± SD | Min | Max | Avg ± SD | Min | Max | Avg ± SD | Min | Max | Avg ± SD | Min | Max |
| **N-BP-5** | 33.5 ± 3.9 | 26.7 | 39.9 | 36.5 ± 0.7 | 35.0 | 37.2 | 56.6 ± 15.9 | 44.4 | 114.6 | 59.9 ± 2.3 | 55.9 | 64.2 |
| **S-BP-5** | 36.6 ± 3.5 | 30.4 | 41.8 | 38.6 ± 1.0 | 37.2 | 40.4 | 99.8 ± 41.5 | 54.8 | 248.5 | 66.5 ± 6.0 | 54.2 | 78.8 |
| **W-BP-5** | 32.8 ± 3.5 | 27.5 | 38.6 | 34.1 ± 1.7 | 31.8 | 36.2 | 51.2 ± 4.9 | 44.0 | 64.2 | 58.2 ± 3.0 | 52.3 | 63.0 |
| **N-BB-5** | 34.0 ± 3.6 | 29.4 | 40.9 | 41.9 ± 1.8 | 38.8 | 45.1 | 54.5 ± 6.7 | 45.0 | 71.2 | 63.5 ± 5.0 | 54.9 | 74.5 |
| **S-BB-5** | 28.6 ± 4.5 | 21.9 | 43 | 74.5 ± 31.0 | 37.1 | 13.6 | 49.1 ± 7.0 | 38.9 | 63.7 | 57.2 ± 4.9 | 50.7 | 66.0 |
| **E-BB-5** | 60.5 ± 19.4 | 32.5 | 85.0 | 42.3 ± 0.7 | 41.0 | 43.4 | 71.0 ± 37.3 | 50.1 | 187.5 | 81.8 ± 34.8 | 60.2 | 183.6 |
| **MID** | 33.6 ± 5.5 | 25.9 | 42.7 | 69.9 ± 54.6 | 33.9 | 186.4 | 58.7 ± 8.7 | 45.7 | 81.6 | 62.7 ± 8.2 | 54.3 | 91.8 |
| **S-BP-25** | Probe malfunction | | | | | | | | | | | |
| **S-BB-25** | 29.7 ± 3.7 | 23.4 | 40.1 | 59.3 ± 18.2 | 34.1 | 100.5 | 53.6 ± 8.4 | 39.1 | 74.3 | 60.6 ± 4.5 | 60.6 | 69.3 |

**Table 10.** Turbidity (NTU) values for replicate harvest #2 from 30 minutes pre-harvest to 30 minutes post-harvest at sondes located adjacent to the bottom plant (BP) and bottom bag (BB) culture sites. Harvest time for sunray venus clams in bottom bags was 12 minutes, while bottom-planted sunray venus clams required 42 minutes to harvest using the pump-driven device. Sonde position is noted as direction, culture method, and distance from the adjacent culture site (e.g., N-BP-5). The sonde located between culture sites is designated as MID. Sondes were also positioned 25 feet down current from each culture site. These sondes are designated as N-BP-25 and N-BB-25 as their position was dependent on the incoming tide.

| Sonde Location | Turbidity (NTU) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 30 min Pre-Harvest | | | Bottom Bag Harvest | | | Bottom Plant Harvest | | | 30 min Post-Harvest | | |
| | Avg ± SD | Min | Max | Avg ± SD | Min | Max | Avg ± SD | Min | Max | Avg ± SD | Min | Max |
| **N-BP-5** | 12.0 ± 6.5 | 8.3 | 40.7 | 14.6 ± 3.1 | 12.4 | 21.2 | 37.2 ± 33.2 | 10.4 | 175.6 | 17.2 ± 9.6 | 12.2 | 67.3 |
| **S-BP-5** | 14.5 ± 5.2 | 10.0 | 30.0 | 14.3 ± 1.2 | 11.8 | 16.2 | 18.1 ± 17.9 | 10.9 | 104.3 | 15.4 ± 0.9 | 13.0 | 17.3 |
| **W-BP-5** | 13.9 ± 4.4 | 10.9 | 27.1 | 14.3 ± 0.7 | 13.0 | 15.4 | 13.2 ± 1.1 | 12.0 | 18.0 | 16.5 ± 1.2 | 13.6 | 18.9 |
| **N-BB-5** | 14.4 ± 4.7 | 10.9 | 31.9 | 60.7 ± 52.1 | 13.7 | 175.4 | 26.4 ± 23.9 | 12.3 | 125.5 | 20.4 ± 8.6 | 14.3 | 48.2 |
| **S-BB-5** | 10.5 ± 4.9 | 4.6 | 23.7 | 7.9 ± 1.2 | 6.4 | 9.7 | 6.2 ± 0.8 | 4.9 | 8.3 | 9.2 ± 1.0 | 7.1 | 11.3 |
| **E-BB-5** | 17.0 ± 8.6 | 9.8 | 46.2 | 58.3 ± 44.6 | 15.2 | 141.5 | 12.0 ± 2.6 | 10.6 | 26.7 | 15.1 ± 1.8 | 12.5 | 23.1 |
| **MID** | 30.3 ± 4.2 | 26.3 | 45.6 | 31.6 ± 1.9 | 29.7 | 36.1 | 36.8 ± 15.2 | 27.0 | 74.1 | 30.9 ± 1.2 | 28.3 | 33.6 |
| **N-BP-25** | Probe malfunction | | | | | | | | | | | |
| **N-BB-25** | 7.8 ± 4.4 | 5.2 | 24.2 | 22.7 ± 14.6 | 7.8 | 51.2 | 27.2 ± 19.6 | 7.5 | 87.8 | 15.5 ± 7.1 | 9.5 | 44.9 |

**Table 11.** Turbidity (NTU) values for replicate #3 harvest from 30 minutes pre-harvest to 30 minutes post-harvest at sondes located adjacent to the bottom plant (BP) and bottom bag (BB) culture sites. Harvest time for sunray venus clams in bottom bags was 11 minutes, while bottom-planted sunray venus clams required 48 minutes to harvest using the pump-driven device. Sonde position is noted as direction, culture method, and distance from the adjacent culture site (e.g., N-BP-5). The sonde located between culture sites is designated as MID. Sondes were also positioned 25 feet down current from each culture site. These sondes are designated as N-BP-25 and N-BB-25 as their position was dependent on the incoming tide.

| Sonde Location | Turbidity (NTU) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 30 min Pre-Harvest | | | Bottom Bag Harvest | | | Bottom Plant Harvest | | | 30 min Post-Harvest | | |
| | Avg ± SD | Min | Max | Avg ± SD | Min | Max | Avg ± SD | Min | Max | Avg ± SD | Min | Max |
| **N-BP-5** | 5.3 ± 1.3 | 3.7 | 8.3 | 9.7 ± 3.0 | 4.3 | 12.8 | 20.0 ± 10.7 | 8.7 | 55.1 | 21.6 ± 1.8 | 18.4 | 25.8 |
| **S-BP-5** | 3.9 ± 1.3 | 2.0 | 6.7 | 10.5 ± 2.2 | 5.7 | 12.6 | 21.6 ± 15.4 | 8.0 | 84.7 | 22.3 ± 1.8 | 19.8 | 26.3 |
| **W-BP-5** | 9.4 ± 1.3 | 7.6 | 11.8 | 15.4 ± 1.6 | 12.4 | 18.1 | 20.8 ± 3.8 | 14.1 | 27.7 | 26.9 ± 1.5 | 24.3 | 29.5 |
| **N-BB-5** | 4.8 ± 1.4 | 2.8 | 7.8 | 41.0 ± 31.5 | 3.6 | 99.0 | 27.7 ± 19.8 | 9.0 | 123.1 | 22.6 ± 2.5 | 18.6 | 30.6 |
| **S-BB-5** | 10.9 ± 1.6 | 8.6 | 13.7 | 15.7 ± 0.91 | 14.0 | 16.9 | 21.7 ± 4.1 | 15.2 | 28.7 | 28.9 ± 2.1 | 25.8 | 32.8 |
| **E-BB-5** | 7.1 ± 7.1 | 3.2 | 40.3 | 23.5 ± 38.2 | 8.4 | 144.2 | 16.4 ± 4.2 | 9.0 | 25.8 | 23.0 ± 2.0 | 18.7 | 26.4 |
| **MID** | 31.9 ± 1.2 | 30 | 34.4 | 40.6 ± 5.0 | 31.8 | 48.7 | 53.3 ± 17.0 | 36.9 | 116.8 | 49.0 ± 2.4 | 45.7 | 56.5 |
| **N-BP-25** | 9.7 ± 1.5 | 8.1 | 12.8 | 16.5 ± 2.8 | 10.9 | 20.1 | 38.0 ± 24.1 | 14.1 | 130.9 | 28.4 ± 2.2 | 24.2 | 34.0 |
| **N-BB-25** | 10.6 ± 0.9 | 9.6 | 13.3 | 21.3 ± 13.7 | 9.7 | 56.5 | 25.9 ± 9.7 | 13.0 | 57.5 | 22.2 ± 1.3 | 19.8 | 26.0 |

**Table 12.** Turbidity (NTU) values for replicate #4 harvest from 30 minutes pre-harvest to 30 minutes post-harvest at sondes located adjacent to the bottom plant (BP) and bottom bag (BB) culture sites. Harvest time for sunray venus clams in bottom bags was 9 minutes, while bottom-planted sunray venus clams required 35 minutes to harvest using the pump-driven device. Sonde position is noted as direction, culture method, and distance from the adjacent culture site (e.g., N-BP-5). The sonde located between culture sites is designated as MID. Sondes were also positioned 25 feet down current from each culture site. These sondes are designated as N-BP-25 and N-BB-25 as their position was dependent on the incoming tide.

| Sonde Location | Turbidity (NTU) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 30 min Pre-Harvest | | | Bottom Bag Harvest | | | Bottom Plant Harvest | | | 30 min Post-Harvest | | |
| | Avg ± SD | Min | Max | Avg ± SD | Min | Max | Avg ± SD | Min | Max | Avg ± SD | Min | Max |
| **N-BP-5** | 14.6 ± 1.5 | 12.6 | 18.8 | 15.6 ± 2.4 | 13.3 | 20.6 | 52.7 ± 29.6 | 14.5 | 140.5 | 22.2 ± 5.0 | 15.3 | 36.0 |
| **S-BP-5** | 16.5 ± 2.3 | 14 | 22.1 | 16.5 ± 1.9 | 14.6 | 19.9 | 22.8 ± 21.2 | 13.6 | 136.8 | 22.4 ± 5.1 | 16.6 | 33.5 |
| **W-BP-5** | 15.7 ± 2.8 | 12.6 | 25.2 | 15.0 ± 1.6 | 13.9 | 18.8 | 18.8 ± 13.2 | 12.6 | 90.6 | 21.4 ± 4.8 | 15.7 | 30.7 |
| **N-BB-5** | 14.9 ± 1.9 | 12.5 | 19.7 | 65.6 ± 22.6 | 27.4 | 101.1 | 26.9 ± 19.2 | 12.3 | 83.8 | 22.1 ± 5.5 | 15.3 | 38.9 |
| **S-BB-5** | 9.6 ± 2.2 | 7.4 | 15.9 | 10.3 ± 2.2 | 7.8 | 14.1 | 9.2 ± 1.6 | 6.6 | 13.0 | 15.2 ± 4.0 | 9.8 | 23.3 |
| **E-BB-5** | 9.7 ± 1.8 | 7.9 | 15.3 | 17.6 ± 20.0 | 8.3 | 73.4 | 9.5 ± 1.5 | 6.8 | 11.6 | 15.2 ± 4.0 | 10.3 | 23.1 |
| **MID** | 9.7 ± 2.0 | 7.8 | 15.5 | 10.2 ± 2.1 | 8.1 | 13.4 | 17.5 ± 14.0 | 7.5 | 64.0 | 15.5 ± 4.6 | 10.0 | 25.2 |
| **N-BP-25** | 14.3 ± 1.5 | 12.5 | 18.6 | 21.7 ± 7.2 | 14.4 | 35.5 | 45.5 ± 25.7 | 14.7 | 111.5 | 22.7 ± 6.7 | 16.9 | 50.4 |
| **N-BB-25** | 15.4 ± 2.3 | 12.7 | 20.4 | 34.0 ± 20.1 | 17.4 | 71.2 | 36.0 ± 16.4 | 11.3 | 71.7 | 23.0 ± 5.2 | 16.4 | 36.1 |

**Table 13**. Maximum observed turbidity values for all replicates combined 48 hours before, during, and 48 hours post-harvest replicates at sondes located adjacent to the bottom plant (BP) and bottom bag (BB) culture sites. Sonde position is noted as direction, culture method, and distance from the adjacent culture site (e.g., N-BP-5). The sonde located between culture sites is designated as MID. Sondes were also positioned 25 feet down current from each culture site. These sondes are designated as BP-25 and BB-25 as their position (either north or south) was dependent on whether harvesting occurred on an incoming or outgoing tide.

| Sonde Location | Maximum Turbidity (NTU) | | | |
|---|---|---|---|---|
| | 48-Hours Pre-Harvest | Bottom Bag Harvest | Bottom Plant Harvest | 48-Hours Post-Harvest |
| **N-BP-5** | 82.5 | 37.2 | 175.6 | 110.1 |
| **S-BP-5** | 85.5 | 40.4 | 248.5 | 83.5 |
| **W-BP-5** | 83.3 | 36.2 | 90.6 | 73.8 |
| **N-BB-5** | 78.3 | 175.4 | 125.5 | 87.5 |
| **S-BB-5** | 63.2 | 16.9 | 63.7 | 71.7 |
| **E-BB-5** | 83.6 | 141.5 | 187.5 | 68.3 |
| **MID** | 80.6 | 186.4 | 116.8 | 92.1 |
| **BP-25** | 102.9 | 35.5 | 130.9 | 51.2 |
| **BB-25** | 99.1 | 100.5 | 87.8 | 72.0 |

**Table 14.** Average, minimum, and maximum turbidity values for sondes located 5 feet from the commercial test area during a simulated harvest (35 minutes) and 24 hours pre- and post-harvest.

| Sonde Location | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 24 Hours Pre-Harvest | | | Harvest (35 min) | | | 24 Hours Post-Harvest | | |
| | Avg ±SD | Min | Max | Avg ±SD | Min | Max | Avg ±SD | Min | Max |
| **North, N-5** | 28.5 ±10.2 | 13.1 | 68.6 | 24.0 ±10.2 | 17.7 | 60.1 | 31.9 ±20.8 | 13.3 | 135.5 |
| **South, S-5** | 28.7 ±10.3 | 12.9 | 65.9 | 40.2 ±19.1 | 17.7 | 98.2 | 33.1 ±22.2 | 12.5 | 155.2 |
| **East, E-5** | 28.2 ±9.7 | 13.5 | 64.1 | 19.7 ±4.6 | 17.3 | 46.8 | 29.7 ±17.4 | 12.8 | 132.9 |
| **West, W-5** | 23.4 ±9.8 | 7.7 | 66.3 | 23.6 ±9.5 | 13.2 | 47.5 | 26.4 ±20.6 | 7.5 | 126.8 |

**Table 15.** Average, minimum and maximum turbidity values for sondes located 25 feet from the commercial test area during a simulated harvest (35 minutes) and 24 hours pre- and post-harvest.

| Sonde Location | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 24 Hours Pre-Harvest | | | Harvest (35 min) | | | 24 Hours Post-Harvest | | |
| | Avg ±SD | Min | Max | Avg ± SD | Min | Max | Avg ± SD | Min | Max |
| **North, N-25** | 27.9 ±9.9 | 13.4 | 67.0 | 19.0 ±1.5 | 17.5 | 25.2 | 32.0 ±21.9 | 12.4 | 138.8 |
| **South, S-25** | 23.5 ±10.3 | 7.9 | 67.9 | 20.4 ±11.6 | 12.3 | 60.3 | 26.8 ±21.4 | 7.1 | 123.1 |
| **East, E-25** | 26.2 ±9.9 | 11.9 | 65.7 | 16.9 ±1.0 | 15.0 | 19.2 | 29.9 ±20.8 | 10.3 | 134.6 |
| **West, W-25** | 24.3 ±10.4 | 8.6 | 60.4 | 14.4 ±1.3 | 12.6 | 17.7 | 27.8 ±21.6 | 8.0 | 143.9 |

**Table 16.** Average, minimum and maximum turbidity values for sondes located 45 feet from the commercial test area during a simulated harvest (35 minutes) and 24 hours pre- and post-harvest.

| Sonde Location | Turbidity (NTU) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 24 Hours Pre-Harvest | | | Harvest (35 (min) | | | 24 Hours Post-Harvest | | |
| | Avg ±SD | Min | Max | Avg ±SD | Min | Max | Avg ±SD | Min | Max |
| **Southeast, SE-45** | 23.6 ±10.1 | 7.9 | 66.5 | 13.8 ±1.4 | 11.5 | 16.9 | 26.8 ±20.7 | 7.8 | 128.6 |
| **South, S-45** | 28.4 ±10.2 | 13.1 | 72.0 | 19.1 ±1.4 | 17.3 | 24.6 | 31.1 ±19.6 | 13.1 | 142.8 |
| **Southwest, SW-45** | 24.5 ±10.1 | 8.8 | 61.7 | 21.2 ±7.7 | 12.6 | 46.4 | 27.3 ±19.4 | 9.2 | 150.0 |

**Table 17.** Averages and standard deviations (±SD) of soil properties at sites ($n$=4) prior to planting sunray venus clams under bottom nets and in bottom bags. Data were analyzed by t-tests.

| Culture Method | Soil Properties (%) | | |
|---|---|---|---|
| | Sand | Fines | Organic Matter |
| **Bottom Plant** | 97.2 ± 0.02 | 2.77 ± 0.02 | 0.96 ± 0.002 |
| **Bottom Bag** | 96.7 ± 0.04 | 3.23 ± 0.04 | 1.17 ± 0.01 |
| $t$ value | -1.33 | 1.33 | 1.63 |
| $p$ value | 0.2324 | 0.2324 | 0.1552 |

**Table 18.** Averages and standard deviations (±SD) of soil properties at the reference (unfarmed) sites prior to planting sunray venus clams ($n$=8) and at harvest ($n$=4). Data were analyzed by t-tests.

| Collection Period | Reference Soil Properties (%) | | |
|---|---|---|---|
| | Sand | Fines | Organic Matter |
| **Plant** | 96.7 ± 0.03 | 3.05 ± 0.03 | 1.06 ± 0.01 |
| **Harvest** | 97.72 ± 0.02 | 2.28 ± 0.02 | 0.84 ± 0.003 |
| $t$ value | -2.29 | 2.29 | 2.06 |
| $p$ value | 0.0449 | 0.0449 | 0.0665 |

**Table 19.** Averages and standard deviations (±SD) of soil properties sampled at the culture sites and reference (unfarmed) sites (*n*=4/treatment/sampling period) at harvest (Wk 0) and at four (Wk 4) and eight (Wk 8) weeks post-harvest. Data were analyzed by repeated measures ANOVA and Tukey-Kramer post-hoc tests. Different superscript letters after the standard deviations indicate significant differences in soil properties between culture/harvest methods and reference sites.

| Site | Soil Properties (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sand | | | Silt | | | Clay | | | Organic Matter | | |
| | Wk 0 | Wk 4 | Wk 8 | Wk 0 | Wk 4 | Wk 8 | Wk 0 | Wk 4 | Wk 8 | Wk 0 | Wk 4 | Wk 8 |
| **Reference** | 97.72 ± 0.02 | 95.13 ± 0.46 | 93.48 ± 0.07 [b] | 1.85 ± 0.01 | 3.86 ± 0.55 | 5.15 ± 0.02 [a] | 0.39 ± 0.07 | 0.93 ± 0.01 | 1.28 ± 0.17 | 0.84 ± 0.003 | 0.99 ± 0.03 | 0.80 ± 0.004 [ab] |
| **Bottom Plant** | 97.98 ± 0.02 | 95.49 ± 0.30 | 93.75 ± 0.11 [b] | 1.60 ± 0.01 | 3.23 ± 0.28 | 4.88 ± 0.08 [a] | 0.38 ± 0.07 | 1.24 ± 0.07 | 1.34 ± 0.06 | 0.71 ± 0.02 | 0.67 ± 0.01 | 0.64 ± 0.01 [b] |
| **Bottom Bags** | 97.38 ± 0.18 | 96.07 ± 0.24 | 96.11 ± 0.10 [a] | 1.94 ± 0.14 | 3.21 ± 0.21 | 2.56 ± 0.03 [b] | 0.64 ± 0.08 | 0.71 ± 0.04 | 1.21 ± 0.23 | 1.17 ± 0.004 | 1.05 ± 0.09 | 1.37 ± 0.14 [a] |
| *F* value | 0.47 | 0.65 | 5.21 | 0.28 | 0.63 | 8.91 | 0.51 | 0.81 | 0.04 | 1.63 | 1.35 | 3.99 |
| *p* value | 0.6313 | 0.5343 | 0.0164 | 0.7584 | 0.5442 | 0.0021 | 0.6082 | 0.4596 | 0.9598 | 0.2250 | 0.2848 | 0.0379 |

**Table 20.** Average soil elevations and standard deviations (±SD) of culture sites immediately after harvest (Wk 0) and at four (Wk 4) and eight (Wk 8) weeks post-harvest (*n*=4/treatment/sampling period). Data were analyzed by t-tests.

| **Culture Method Site** | **Soil Elevations (cm)** | | |
|---|---|---|---|
| | **Wk 0** | **Wk 4** | **Wk 8** |
| **Bottom Plant** | -3.70 ± 1.59 | -1.76 ± 0.43 | -1.59 ± 0.37 |
| **Bottom Bag** | 3.75 ± 1.12 | 0.25 ± 0.61 | -0.93 ± 0.15 |
| *t* value | -9.09 | -4.64 | -5.90 |
| *p* value | 0.0028 | 0.0189 | 0.0097 |

**Figure 1.** Harvesting sunray venus clams from a bottom plant using a pump-driven harvester within the UF experimental lease located at the Dog Island High-density Lease Area near Cedar Key, Florida. The 5 horsepower pump was contained in a floating fiberglass box. The harvesting device was manually pulled over the harvest area.

**Figure 2.** Harvesting sunray venus clams from a bottom bag within the UF experimental lease located at the Dog Island High-density Lease Area near Cedar Key, Florida. These pictures were taken during the harvest of field replicate #3.

**Figure 3**. Water quality monitoring sondes positioned around a bottom net (above) and bottom bags (below) prior to harvest. Note sondes were exposed during a minus tide on this harvest date (field replicate #3). Harvesting activities did not begin until 30 minutes after the incoming tide inundated the sondes.

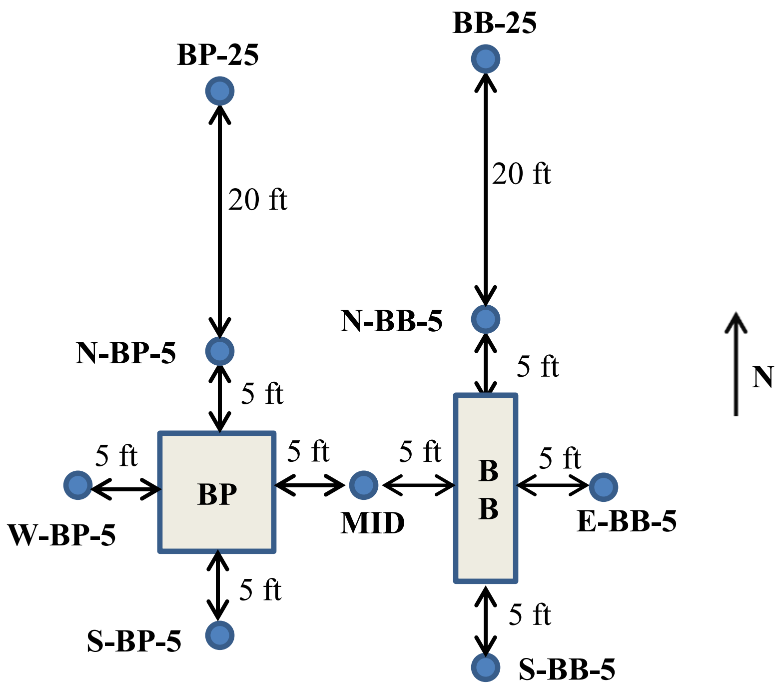



**Figure 4**. Sondes were located at 5 feet intervals from the bottom plant (BP) and bottom bag (BB) harvest sites to the north, south, east, and west. Sonde position is noted as direction, culture method, and distance from the adjacent culture site (e.g., N-BP-5). The sonde located between culture sites is designated as MID. Sondes were also positioned 25 feet down current from each culture site. These sondes are designated BP-25 and BB-25 as their position (either north or south) was dependent on whether harvesting occurred on an incoming or outgoing tide.

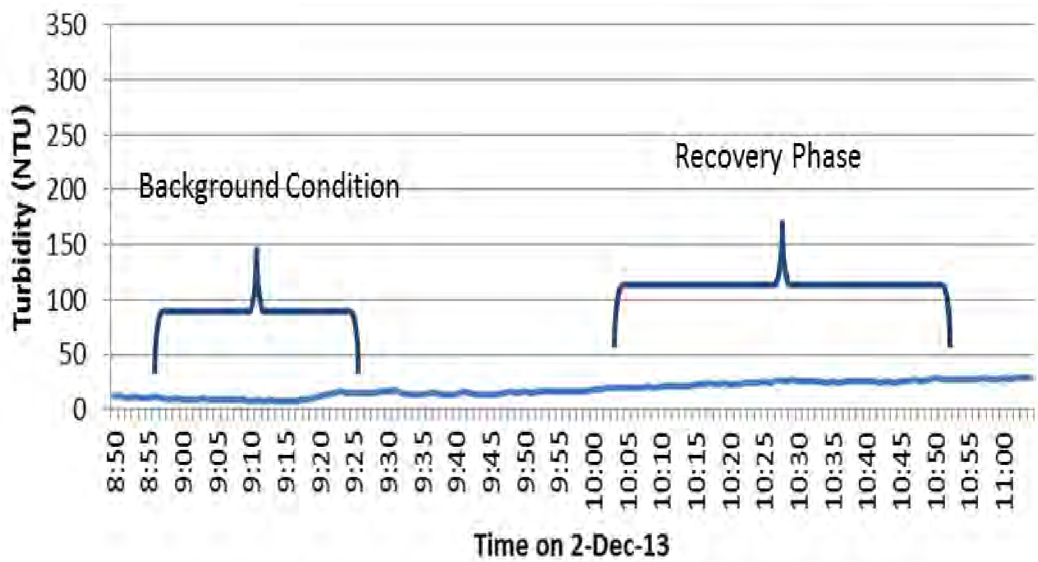



**Figure 5.** Example of baseline correction using turbidity measurements from Sonde W-BP-5 during field replicate 3. Notice the baseline turbidity increases over the course of the tide in the recovery phase. This changing baseline was subtracted from the post-harvest turbidity values to remove the increasing trend in observations and thus accurately determine the return interval.

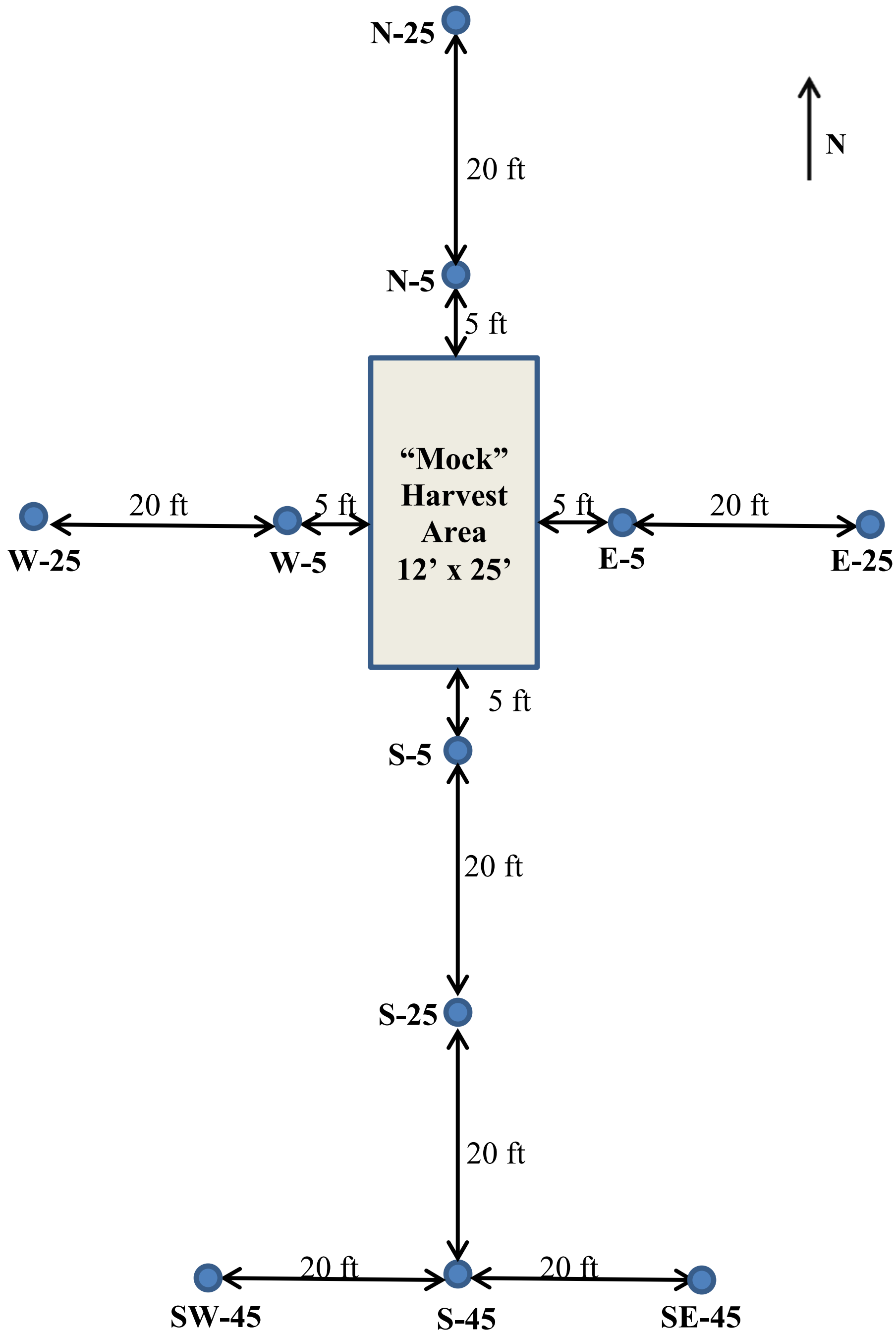



**Figure 6.** Sondes were located at 5 and 25 feet intervals from the commercial-scale harvest area to the north, south, east, and west. Three sondes were also positioned 45 feet south of the harvest area to capture the turbidity plume associated with an outgoing tide. Sonde position is noted as direction and distance from the harvest area (e.g., N-5).


**Figure 7.** Collecting soil cores immediately after harvest to determine soil properties and compare with those established at plant and at adjacent reference (unfarmed) sites.

**Figure 8.** PVC pipe arrays were used to measure soil elevations for determining the extent of the harvest tracks from the bottom plant and bags and to monitor recovery of the soils over time.


**Figure 9.** Sunray venus clams cultured using bottom bags and harvested after 11-13 months in the growout stage. Note misshapen and discolored shells indicating the clams did not completely bury into the bottom sediments.


**Figure 10.** Sunray venus clams cultured using bottom net method and harvested with a pump-driven device after 11-13 months in the growout stage. Note uniformity of harvested product.

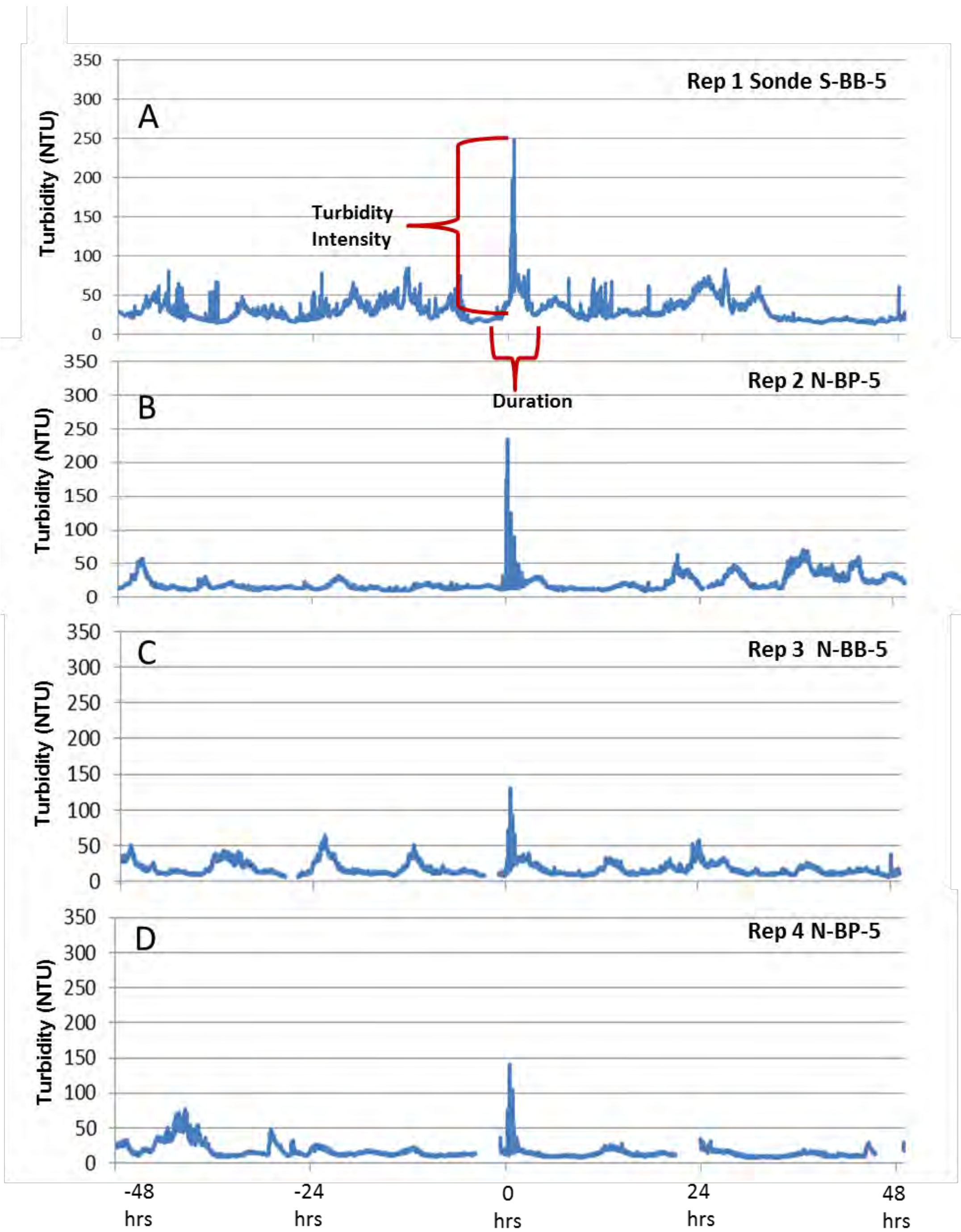



**Figure 11**. Corrected turbidity measurements (NTU) for 48 hours pre and post of each of four combined bag and bottom plant harvest replicates. Center peak is the intensity of the harvest activity (time 0). Note duration of harvest event (red close bracket) in relation to other natural events.(A) indicates experimental replicate 1,(B) replicate 2, (C) replicate 3, and (D) replicate 4.

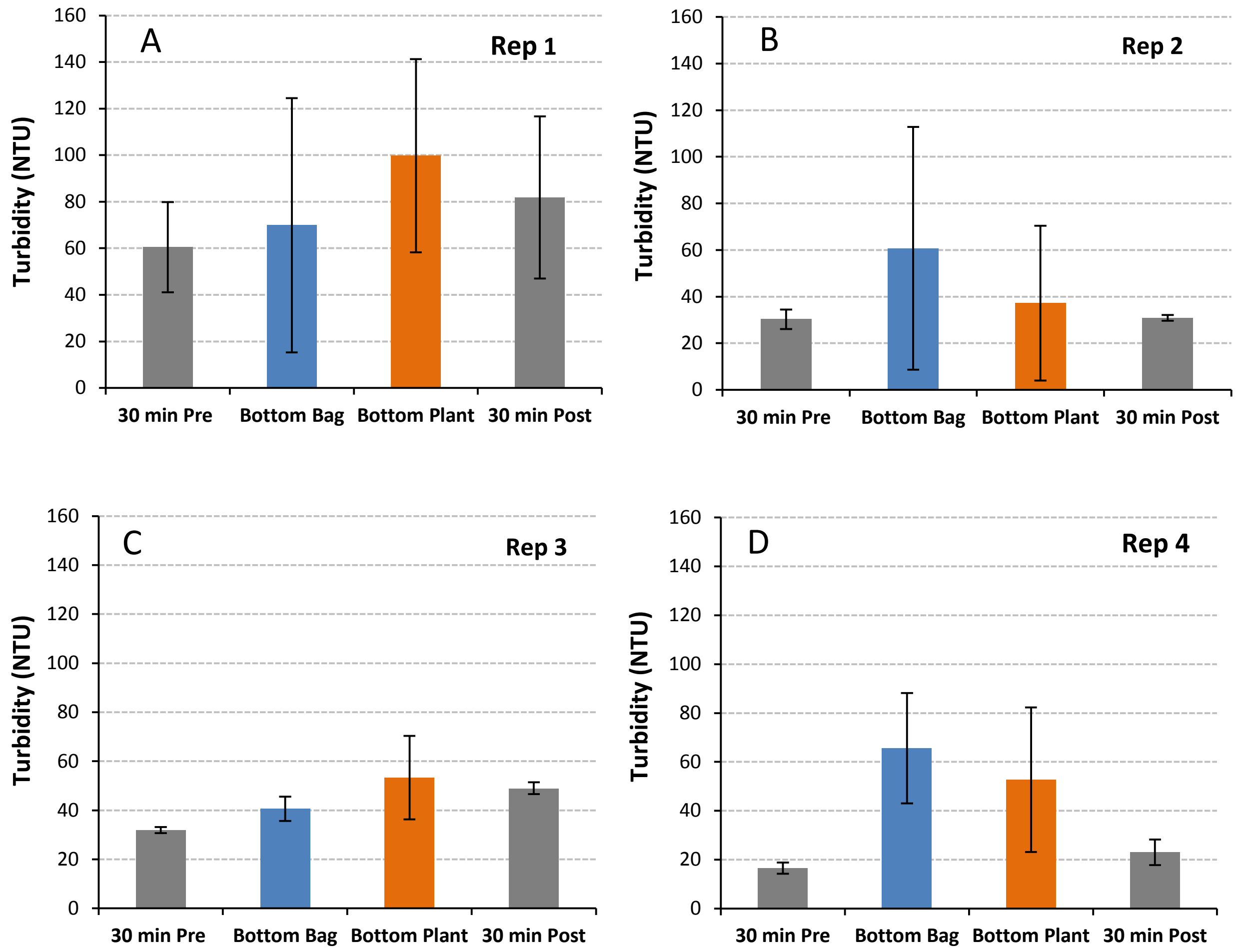



**Figure 12.** Comparison of highest mean turbidity observations for 30 minutes pre-harvest, bottom bag harvest, bottom plant harvest, and 30 minutes post-harvest. (A) indicates experimental replicate 1, (B) replicate 2, (C) replicate 3, and (D) replicate 4.

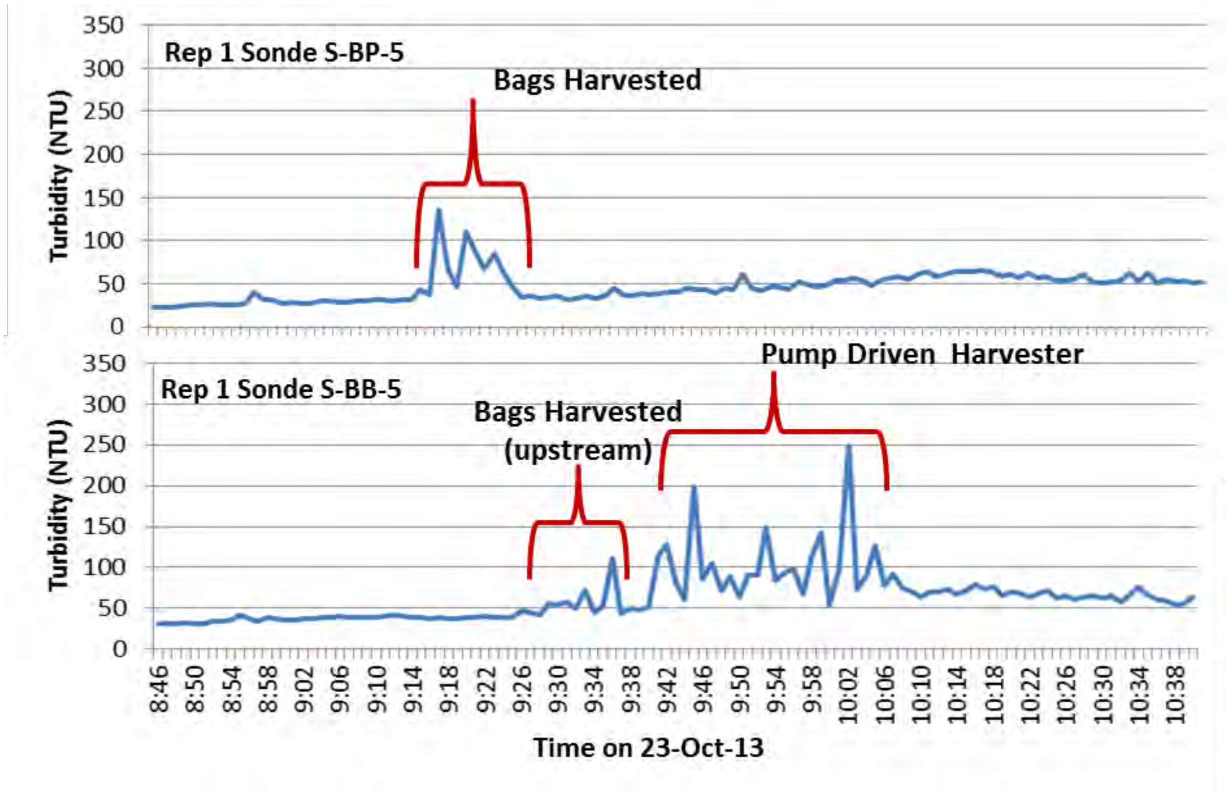



**Figure 13**. Comparison of bag harvest (top graph) and pump-driven harvester (bottom graph) from replicate 1. Turbidity associated with harvesting the bags was determined to return to background level in 2 minutes, while turbidity associated with the use of the pump-driven harvester returned to background in 5 minutes in this replicate. Brackets denote the time frame of harvest activity. Note that due to environmental conditions, the pump harvest was not captured by the S-BP-5 sonde.

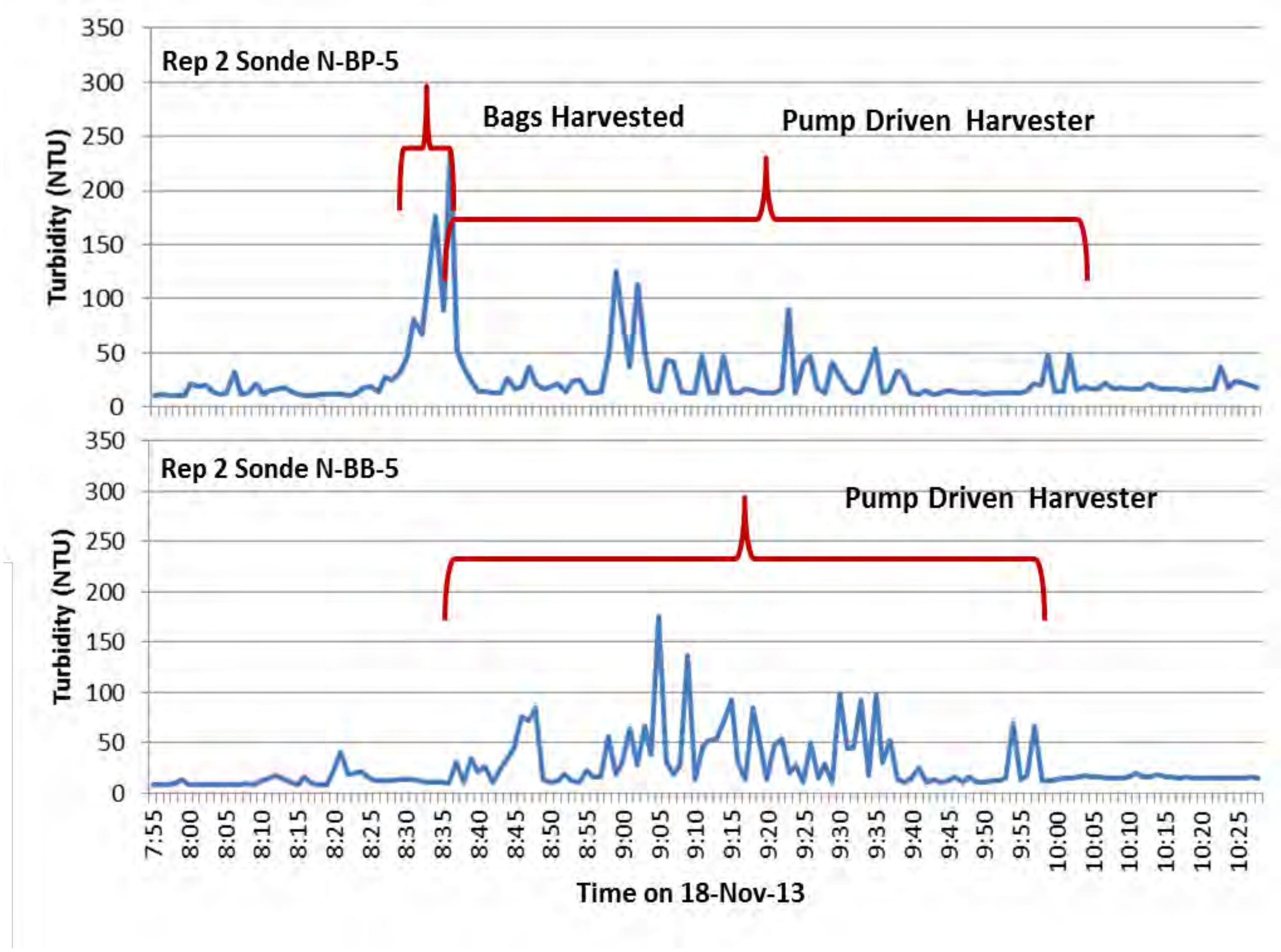



**Figure 14**. Comparison of bag harvest (top graph) and pump-driven harvester (bottom graph) from replicate 2. Return interval for turbidity associated with harvesting the bags was not determined; however, turbidity associated with the use of the pump-driven harvester returned to background in 9 minutes in this replicate. Brackets denote the time frame of harvest activity.

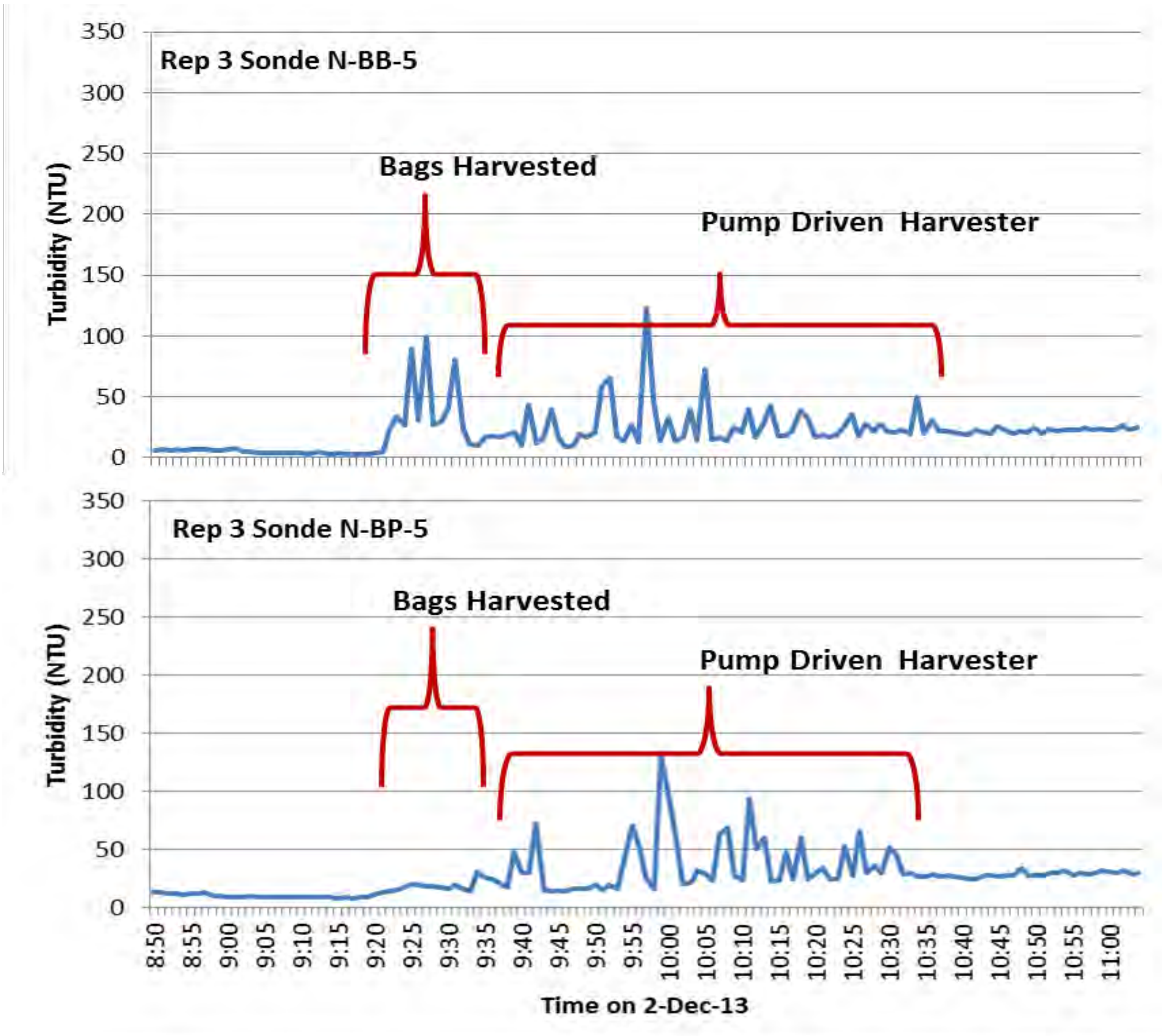



**Figure 15**. Comparison of bag harvest (top graph) and pump-driven harvester (bottom graph) from replicate 3. Return interval for turbidity associated with harvesting the bags was not determined; however, turbidity associated with the use of the pump-driven harvester returned to background in 5 minutes in this replicate. Brackets denote the time frame of harvest activity.

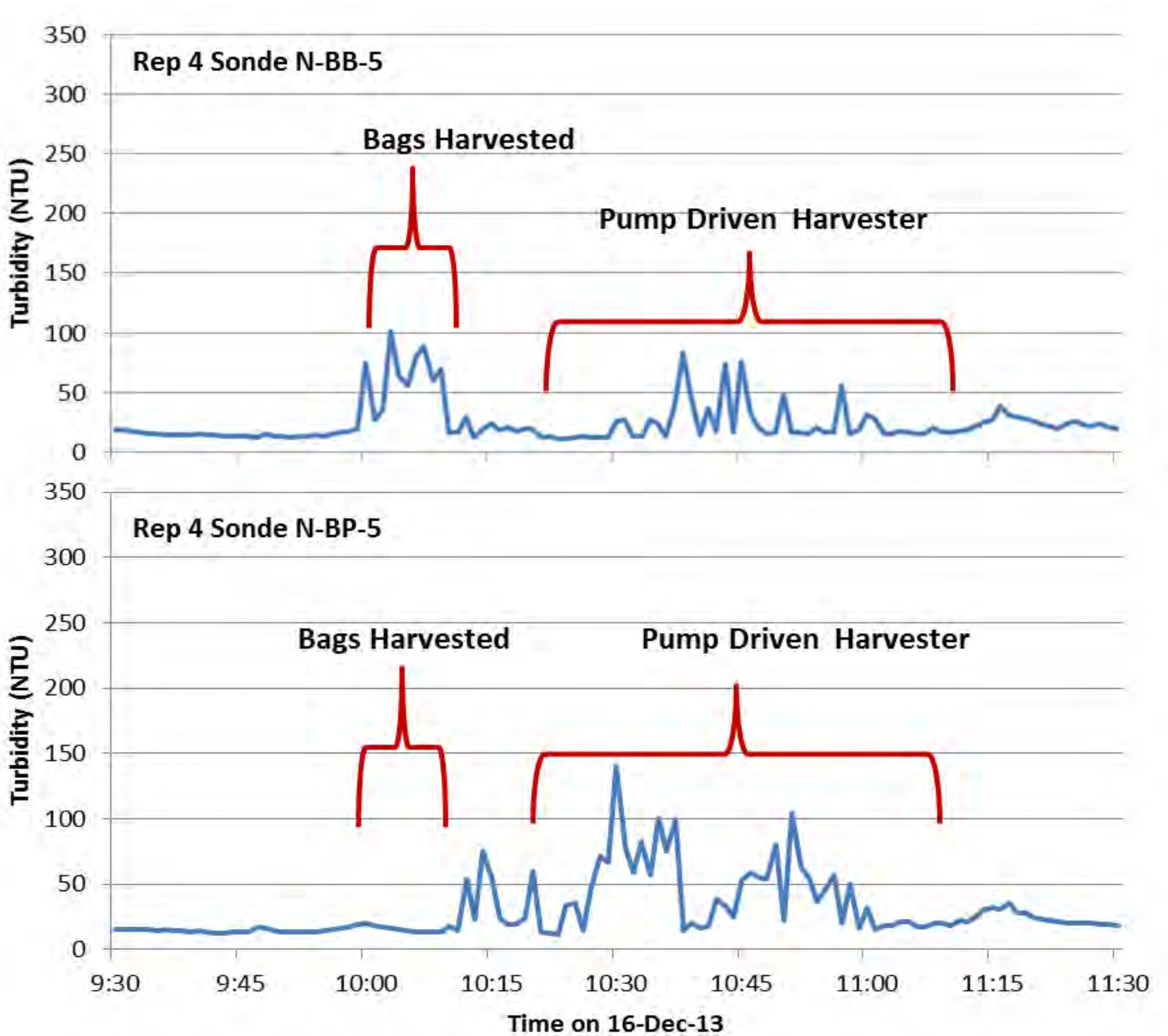



**Figure 16**. Comparison of bag harvest (top graph) and pump-driven harvester (bottom graph) from replicate 4. Turbidity associated with harvesting the bags was determined to return to background level in 5 minutes while turbidity associated with the use of the pump-driven harvester returned to background in 4 minutes in this replicate. Brackets denote the time frame of harvest activity.

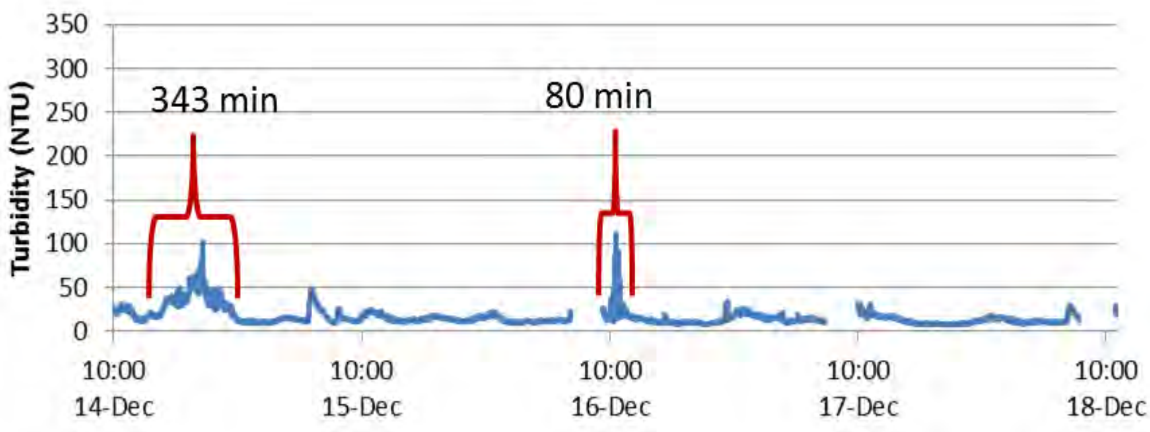



**Figure 17**. Example of duration of natural background turbidity (353 min) in relation to combined bag and bottom plant harvests (80 min).

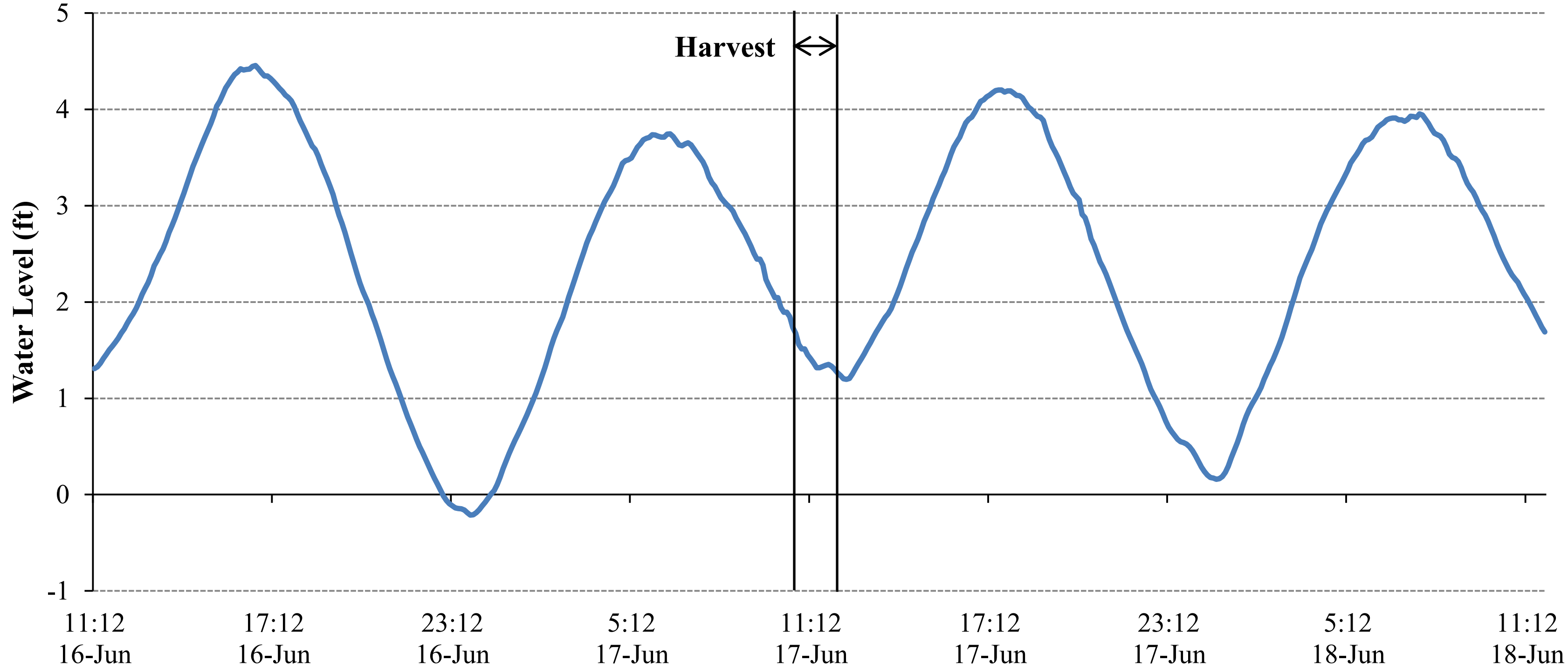



**Figure 18**. Tidal fluctuations measured at the city dock in Cedar Key, Florida (NOAA station 8727520) during harvest (17 June 2014, 10:52-11:46am) and 24 hours pre-and post-harvest.

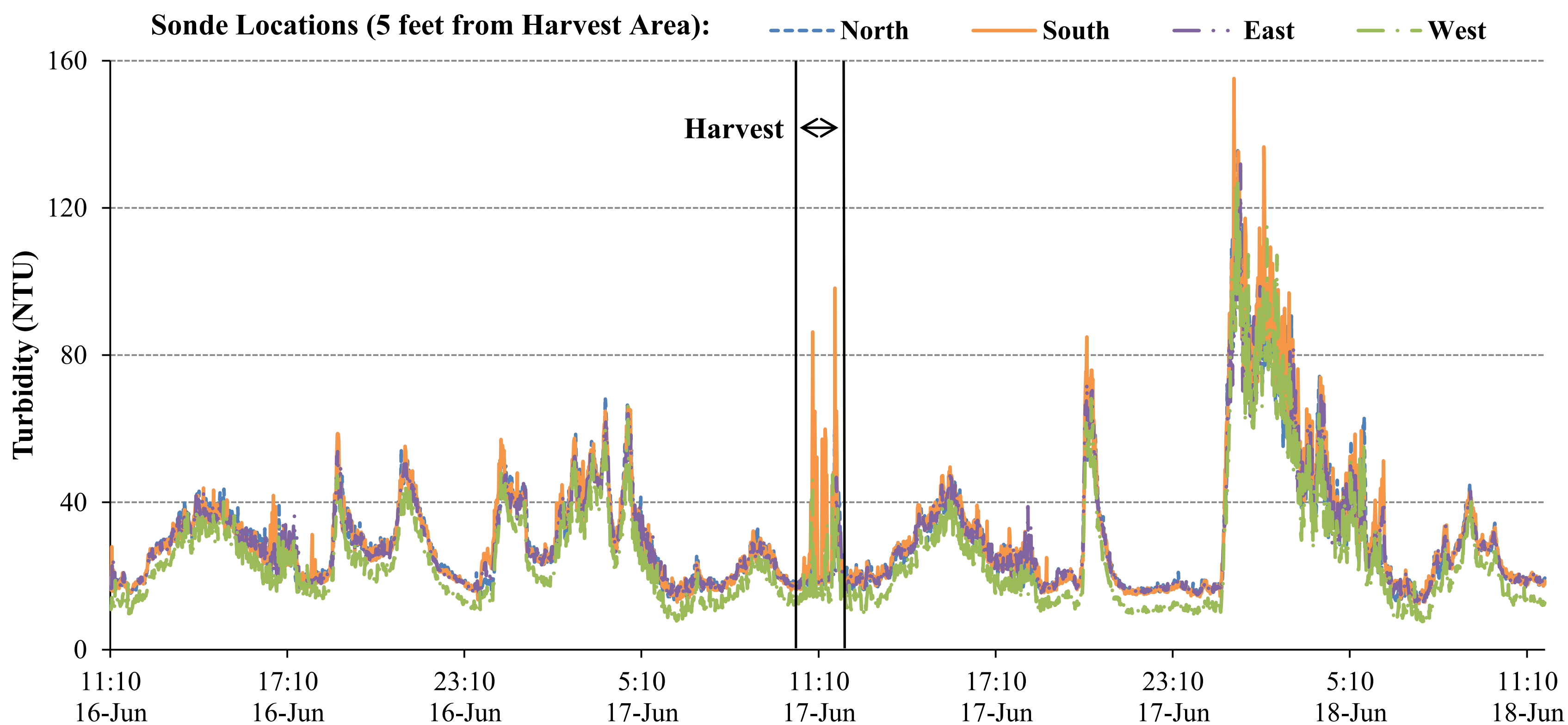



**Figure 19.** Turbidity (NTU) values at sondes located five feet from the commercial test area during harvest (17 June 2014, 10:52-11:46am) and 24-hours pre- and post-harvest.

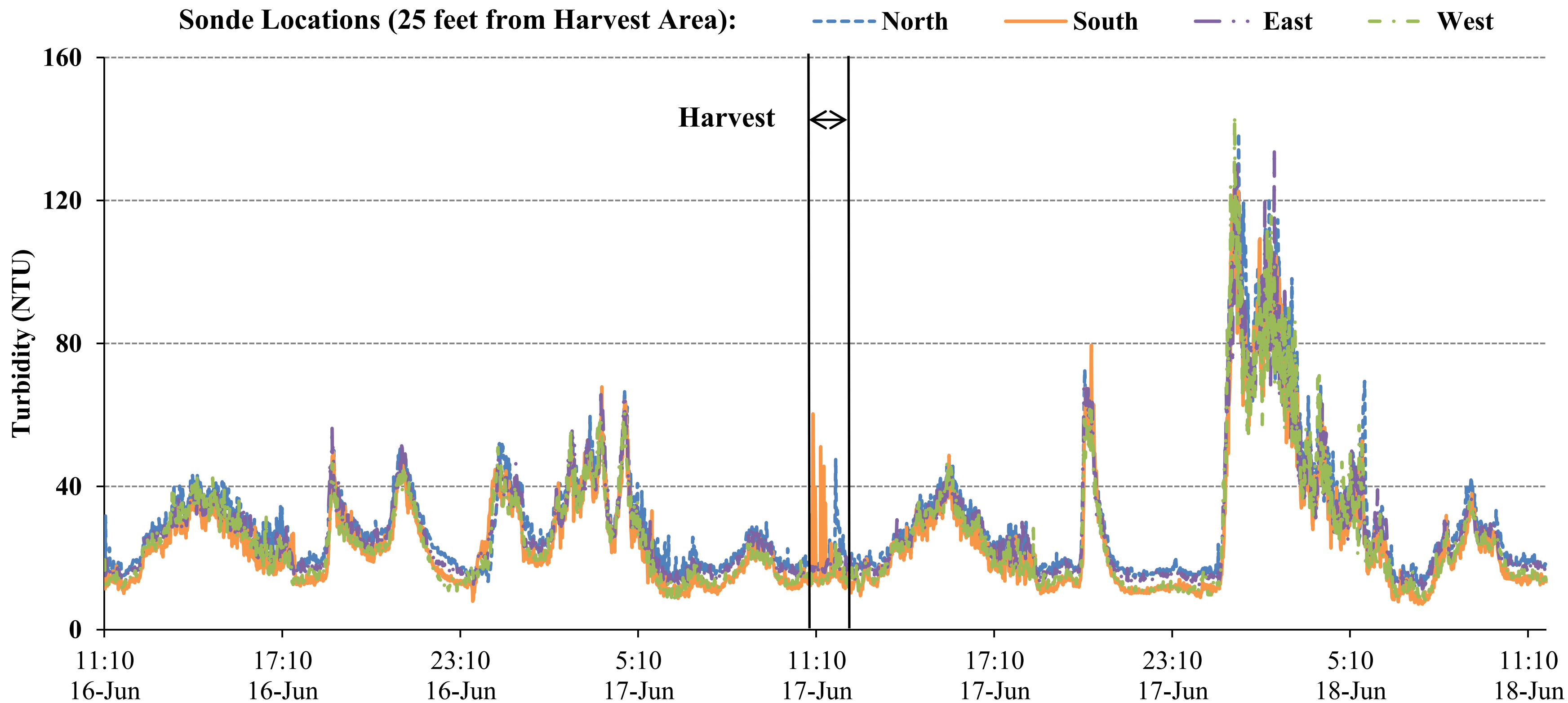



**Figure 20.** Turbidity (NTU) values at sondes located 25 feet from the commercial test area during harvest (17 June 2014, 10:52-11:46am) and 24-hours pre- and post-harvest.

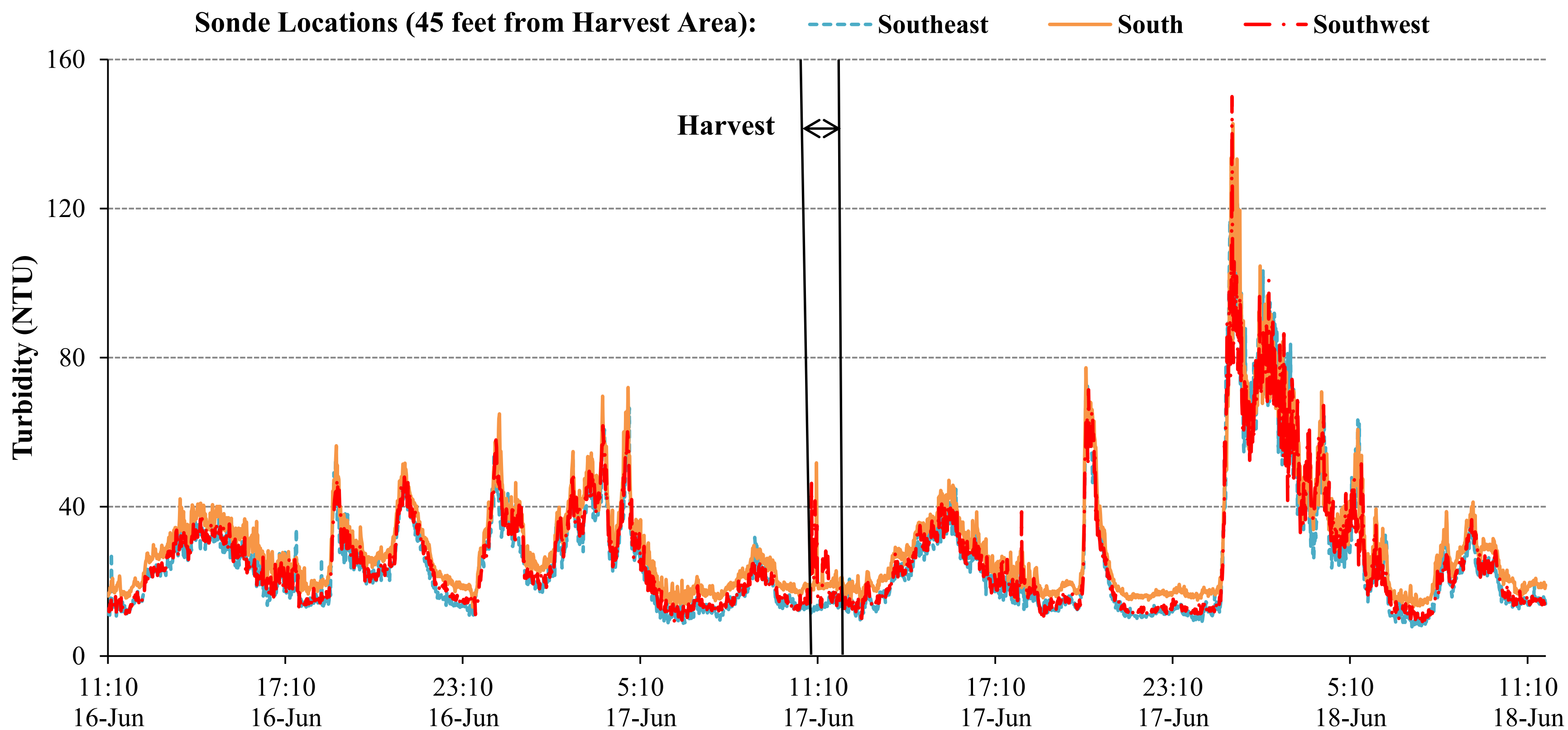



**Figure 21.** Turbidity (NTU) values at sondes located 45 feet from the commercial test area during harvest (17 June 2014, 10:52-11:46am) and 24-hours pre- and post-harvest.

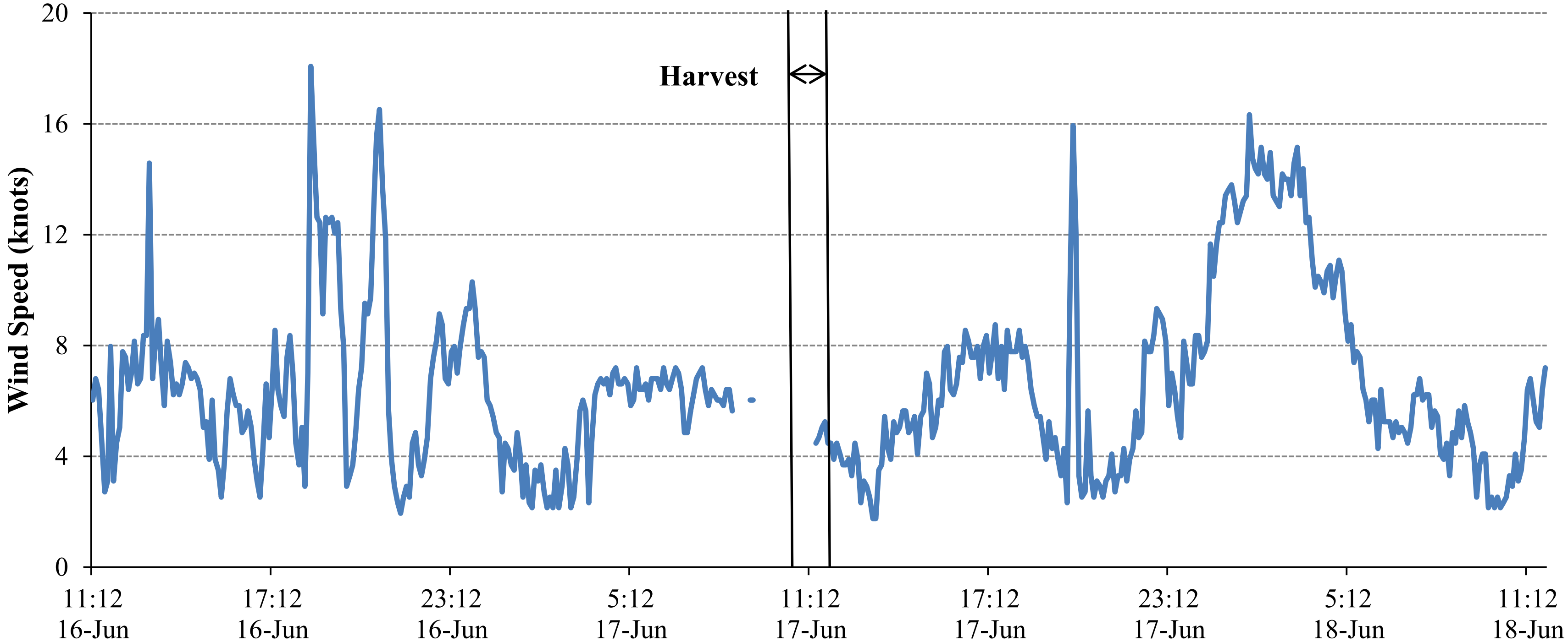



**Figure 22.** Wind speed (knots) measured at the city dock in Cedar Key, FL (NOAA station 8727520) during harvest (17 June 2014, 10:52-11:46am) and 24 hours pre- and post-harvest. The highest wind speed recorded (18.1 knots) occurred on June 16 at 18:30, while the lowest (2.1 knots) occurred on multiple days. Average wind speed during harvest was 4.8±0.4 knots; wind direction was from the ESE and SE.

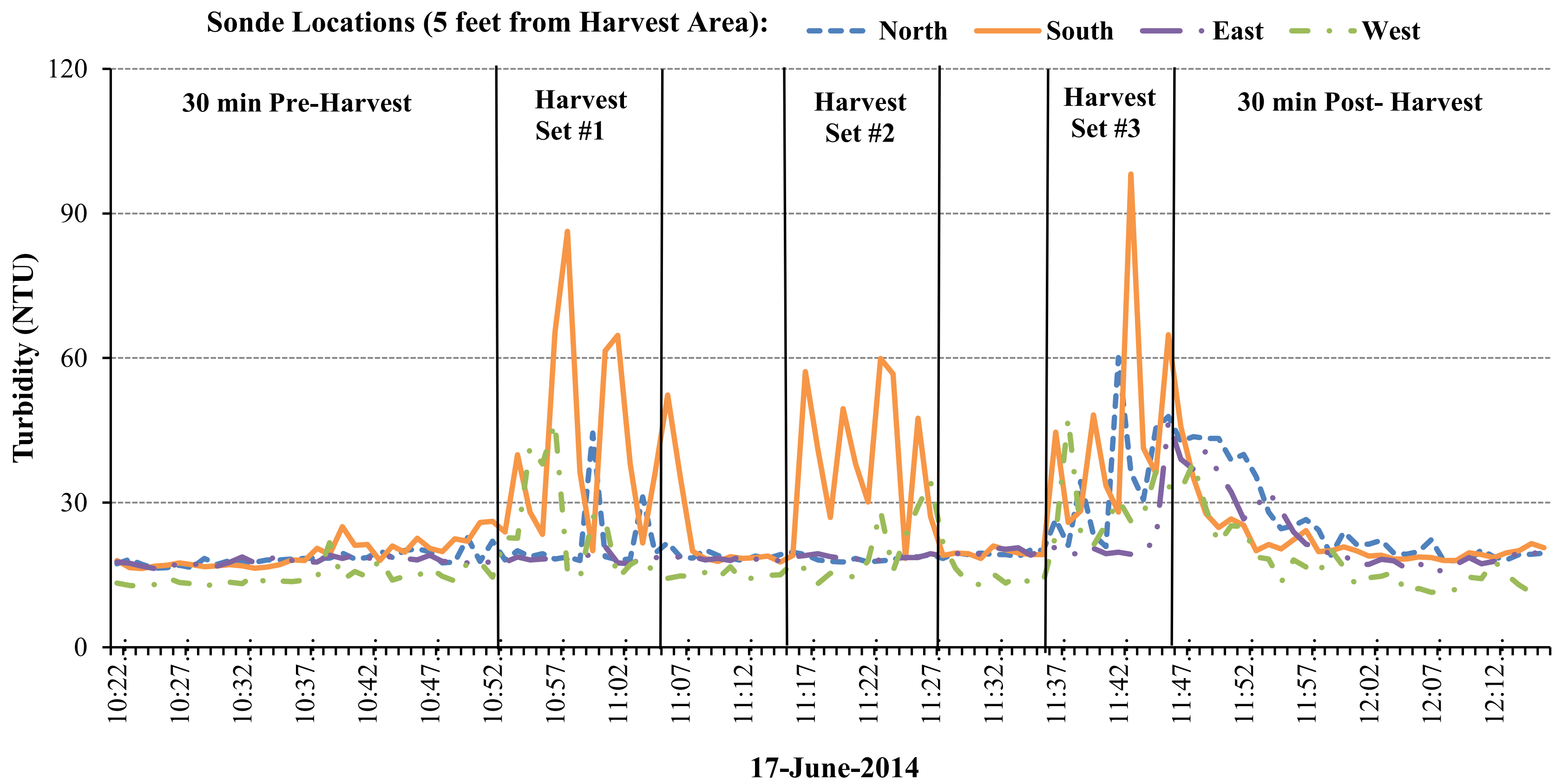



**Figure 23.** Turbidity (NTU) values at sondes located five feet from the commercial test area during harvest (17 June 2014, 10:52-11:46am) and 30 minutes pre- and post-harvest. Each harvest set consisted of eight passes of the pump-driven harvester over the test area.

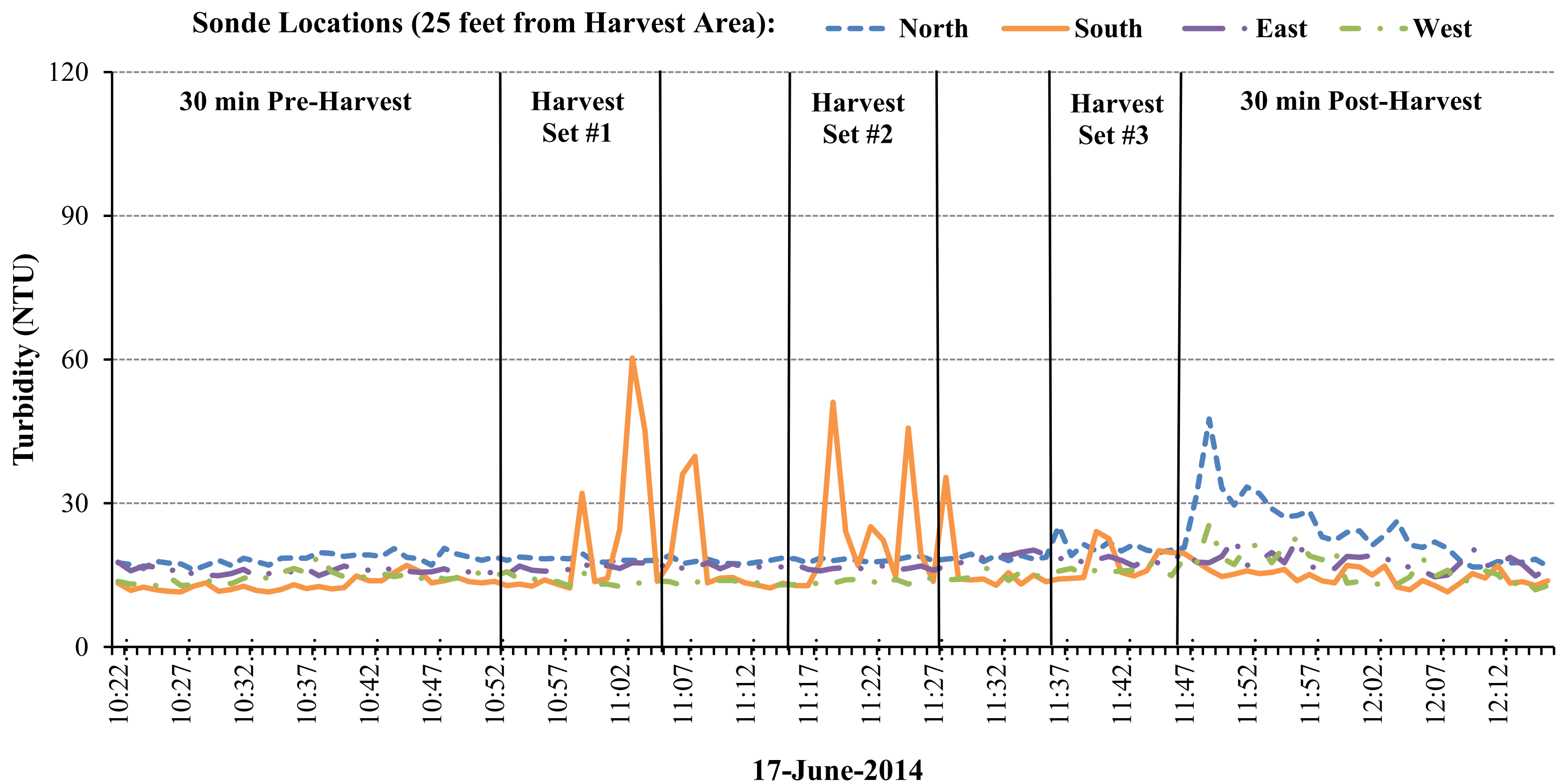



**Figure 24.** Turbidity (NTU) values at sondes located 25 feet from the commercial test area during harvest (17 June 2014, 10:52-11:46am) and 30 minutes pre- and post-harvest. Each harvest set consisted of eight passes of the pump-driven harvester over the test area.

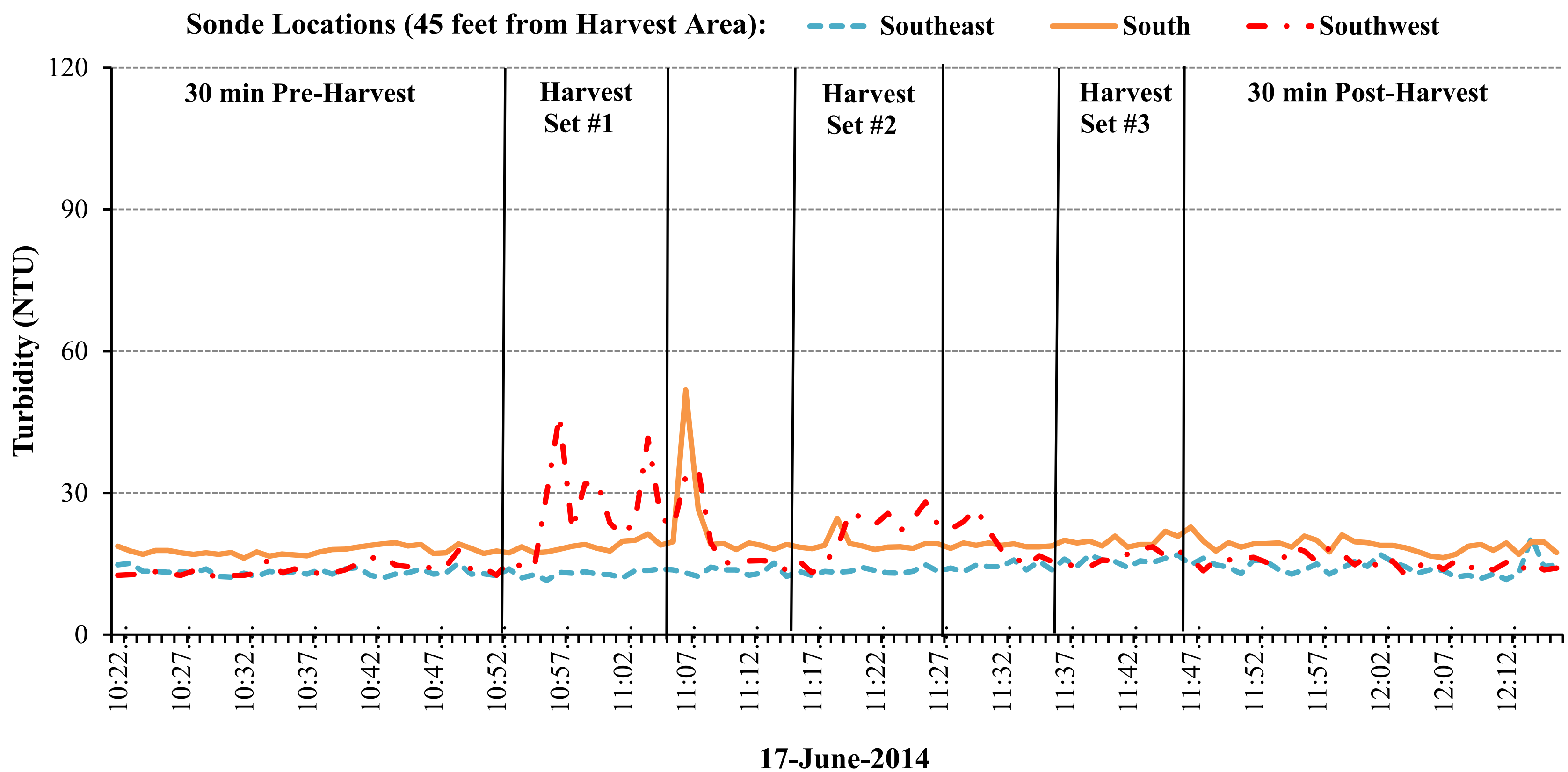



**Figure 25.** Turbidity (NTU) values at sondes located 45 feet from the commercial test area during harvest (17 June 2014, 10:52-11:46am) and 30 minutes pre- and post-harvest. Each harvest set consisted of eight passes of the pump-driven harvester over the test area.

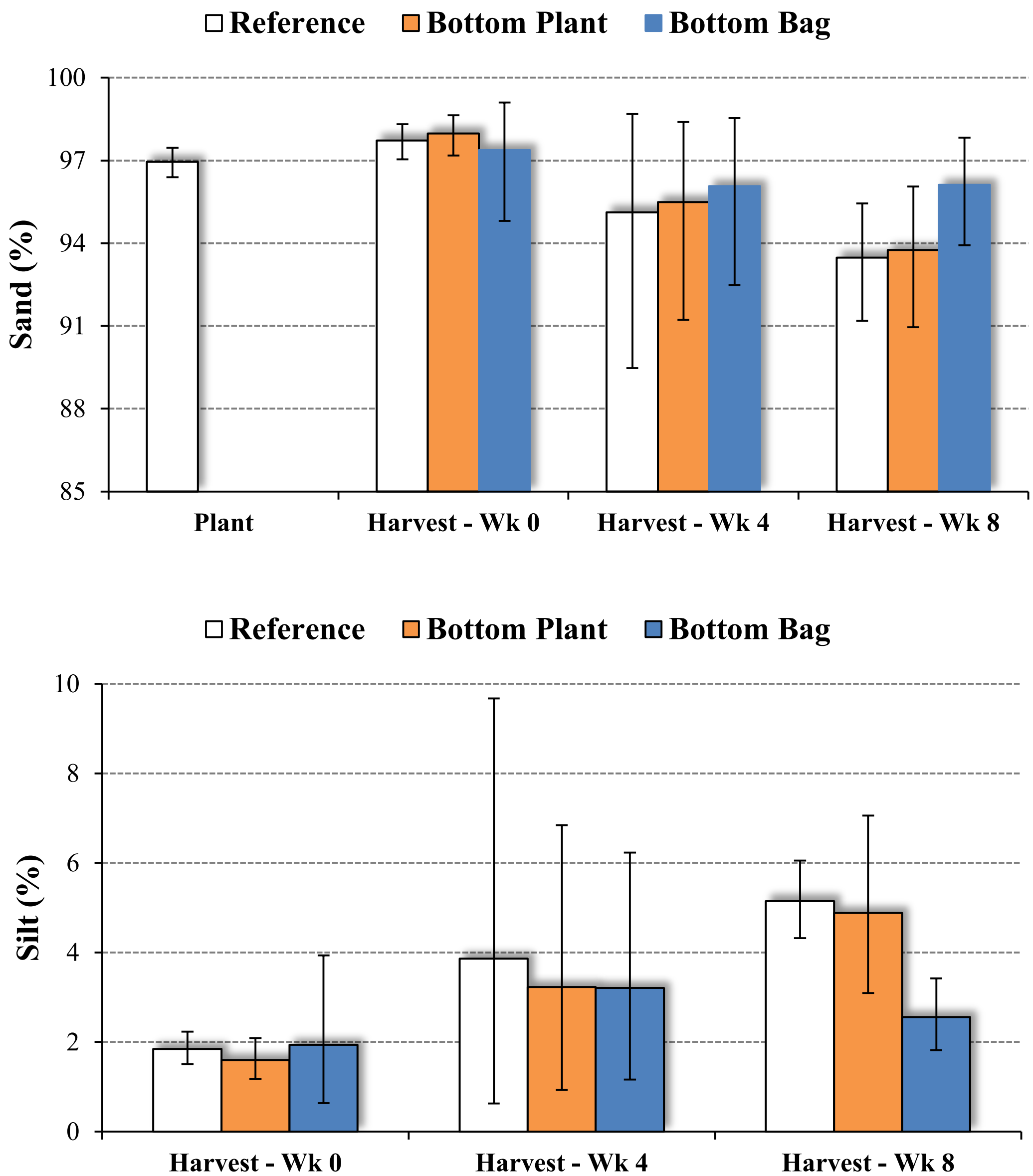



**Figure 26.** Sand and silt content (%) of soils sampled at the culture (bottom plant and bottom bag) sites and reference (unfarmed) sites (*n*=4/treatment/sampling period) at harvest (Wk 0) and at four (Wk 4) and eight (Wk 8) weeks post-harvest. Bars represent 95% confidence intervals.

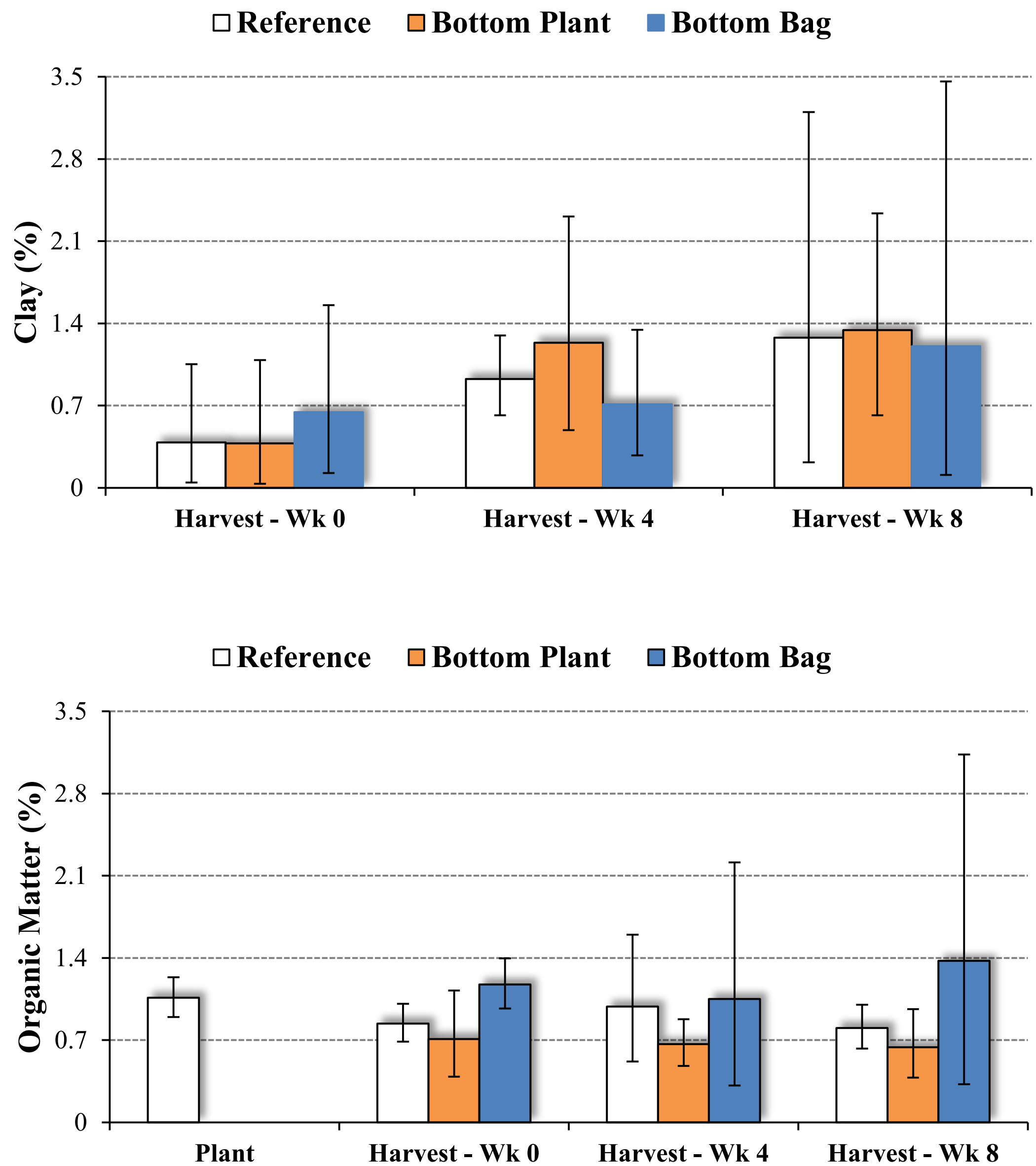



**Figure 27.** Clay content and organic matter (%) of soils sampled at the culture (bottom plant and bottom bag) sites and reference (unfarmed) sites (*n*=4/treatment/sampling period) at harvest (Wk 0) and at four (Wk 4) and eight (Wk 8) weeks post-harvest. Bars represent 95% confidence intervals.

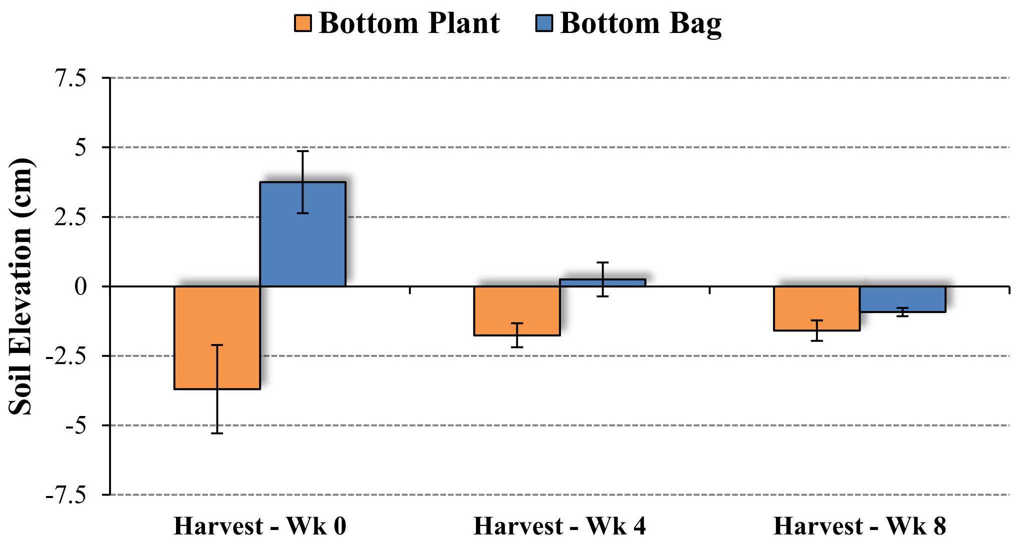
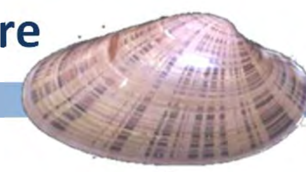



**Figure 28.** Average soil elevations at culture sites (bottom plant and bottom bag) relative to adjacent unfarmed references immediately after harvest (week 0) and 4 and 8 weeks post-harvest. Zero soil elevation represents where average track depth was equal to average reference site elevation. Bars represent standard deviation.

# Appendices

**Appendix A**

# Subaqueous Soil (Sediment) Sampling and Testing for Acceptability of Sunray Venus Culture



## Introduction

The relationship between subaqueous soils (sediments) and sunray venus clam production has been examined in recent studies by University of Florida (UF) researchers. Soils were collected from 18 existing clam leases on the west coast of Florida where test plots of sunray venus clams had been planted. Survivals of >50% were achieved at lease sites with sand content ranging from 88 to 98% and organic matter content ranging from 0.2-1.3%. In a controlled mesocosm (bucket) study conducted at the UF lease near Cedar Key, findings suggested that >85% sand and <3% organic matter content were favorable for sunray venus clam culture. This information will now be used as a tool to aid clam growers in determining the suitability of bottom sediments at their farms for sunray venus clam culture. This soils-based approach is similar to how the USDA National Resources Conservation Service uses soil properties to survey lands best suited for various types of terrestrial crops.

## Subaqueous Soil Test Kit

A subaqueous soil test kit has been assembled for clam growers to collect samples from their lease(s) for analyses of soil properties. The kit consists of the following materials:

1) 8” section of 2”-D PVC pipe
2) Two – 2”-D PVC caps
3) Quart-size ziploc bags
4) Gallon-size ziploc bag(s)
5) Pre-paid addressed shipping box(s)
6) *Subaqueous Soil Sampling and Testing Fact Sheet*
7) *Subaqueous Soil Test Form*

Prior to collecting soil samples, fill out the labels attached to the quart-size bags for each soil sample per lease area. Information required is grower’s name, lease number, soil sample number, and date. Use 1, 2, 3 and subsequent numbers for soil samples collected from the same lease. Also complete the label on the gallon-size bag(s). Soil samples from each lease should be placed inside a gallon bag to minimize possible leakage during shipping.

## Where to Take Subaqueous Soil Samples

Although leases located in high-density lease areas or aquaculture use areas are typically 2.0 acres in size, there are many leases in the state with various acreage. For every 2.0 to 2.5 acres, three soil samples should be collected. Most growers are familiar with their leases and can grossly determine where “sandier” or muddier” soils occur. Select areas within the lease that may be sandy and roughly divide into three sections. Take a soil sample from each section. To be able to relate the soil test results to each sample site, it is recommended that a small PVC pipe or stake be placed at each sample location.

## How to Collect Subaqueous Soil Samples

In order to obtain reliable results from a soil test, the samples must be taken correctly. Soil samples should accurately represent the area being considered for farming. Follow the steps below to properly collect subaqueous soil samples.

**1. At each sample site, insert the core tube (2”-D PVC pipe) into the soil to the red tape mark (about 4” in depth). A zip-tie is also placed at the 4” mark to assist in determining this depth. (Picture A)**

**2. Cover the end of the pipe above the soil by securely fitting the 2” PVC cap. (Picture B)**

**3. Push the tube over to one side until the bottom breaks free. Immediately cap the bottom of the pipe before bringing the sample to the surface.**

**4. At the water surface or in the boat, empty the soil from the tube by removing the bottom cap and inserting the pipe into a quart bag. Then remove the cap from the top of the pipe. The soil sample should slide into the bag. (Picture C)**

**5. Allow time for the contents of the bag to settle before pouring off any clear water. Seal the bag securely. Place the three soil sample bags from each 2.0-2.5 acre area into a gallon bag. Make sure the bags have been properly labeled with name, lease number, sample number, and date sampled.**




## Subaqueous Soil Analyses and Results

Soil samples from shellfish aquaculture leases along with a completed *Soil Test Form* for each 2.0 to 2.5 acre lease area are to be mailed to the UF Soil and Water Science Department, Wetlands Biogeochemistry Laboratory in the addressed, pre-paid shipping box(s) provided. Each sample will be analyzed for soil particle size (sand and fines content), organic matter content, and bulk density (a measure of mass per unit volume). Analyses may take two to four weeks to complete. After which, a soil test report will be provided with information on the results and how they relate to acceptability of sunray venus clam culture.

**Information provided by Todd Osborne[1], Leslie Sturmer[2], and William White[3]**
[1]Univeristy of Florida (UF), Institute of Food and Agricultural Science (IFAS), Soil and Water Sciences Department; [2]UF IFAS Cooperative Extension and Florida Sea Grant; [3]UF IFAS School of Forest Resources and Conservation

# SUBAQUEOUS SOIL TEST FORM

***Complete the contact information below and enclose this form with your soil samples. Providing an email address will accelerate receipt of analyses results. Your contact information will not be shared with any third party.***

SEND THIS FORM AND SAMPLES TO:
UF/ IFAS Soil and Water Science Department
Wetland Biogeochemistry Laboratory
2181 McCarty Hall A, P.O. Box 110290
Gainesville, Florida 32611-0290
Email: osbornet@ufl.edu Telephone: (352) 294-3151

**Name:**________________________________________ **Date:**___________________

**Mailing Address:**_________________________________________________________

**City:**_______________________________________**FL** **Zip:**____________________

**Phone:**__________________________ **Email:**___________________________________

***Complete the information below using one line per soil sample for a 2.0-2.5 acre lease. A separate form must be completed for each lease area. If you are sampling a 4-5 acre lease, continue with this form and number the samples 4, 5, and 6. Provide geographic coordinates in the Latitude and Longitude columns. If you can not, give a relative location where the soil samples were collected in the Location column.***

| Lease # | Sample | Location | Latitude | Longitude |
|---|---|---|---|---|
| | 1 | | | |
| | 2 | | | |
| | 3 | | | |
| | | | | |
| | | | | |
| | | | | |

***Soil tests are provided free through a partnership agreement with the Department of Agriculture and Consumer Services under the Aquaculture Review Council Grant Program, 2013-14 (FDACS Contract No. 020102).***

***In the event of questions, please contact:***

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Shellfish Extension Agent
University of Florida IFAS Sea Grant Extension
P.O. Box 89, Cedar Key, FL 32625
Ph: (352) 543-5057 Email: LNST@ufl.edu

## Appendix B

Two mp4 video files, each 30 seconds recorded with a GoPro Hero2® camera, are provided as separate attachments.

1) This footage is from field harvest replicate #4 conducted on 16 December 2013. The turbidity plume associated with use of the pump-driven harvester (to the far left in this image extracted from the video) is visible but does not extend beyond the harvest area (marked with PVC pipes).

2) This footage is from the commercial-scale harvest conducted on 17 June 2014. The turbidity plume associated with use of the pump-driven harvester (located in the middle of this image extracted from the video) is hard to distinguish from a dense phytoplankton bloom.

## Appendix C

# Subaqueous Soil (Sediment) Acceptability for Sunray Venus (*Macrocallista nimbosa*) Culture: Test Results

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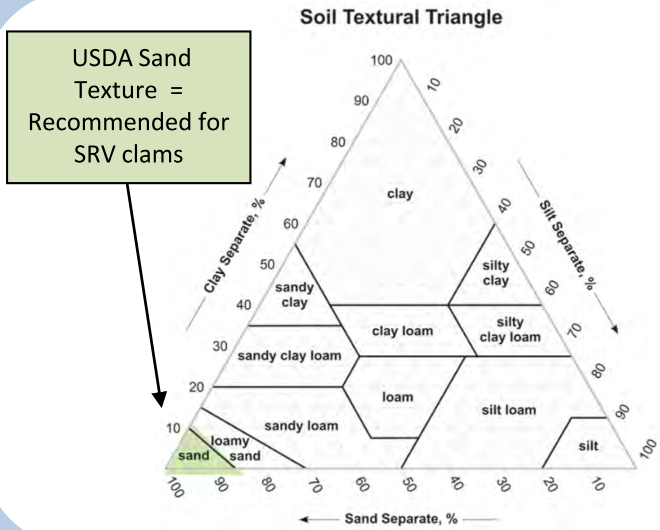
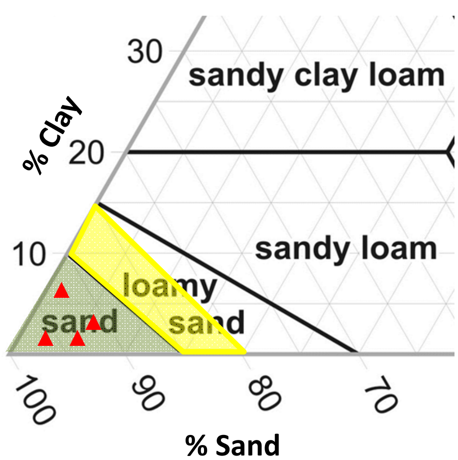



## Introduction

Growth experiments with sunray venus (SRV) in soils ranging from 80% to 100% sand and 0% to 9% organic matter indicated that soils with >85% sand, <10% clay, and <5% organic matter are suited for culturing these clams. Mortality and shell deformities associated with bottom sediments are minimized above 85% sand; growth increases with increased sand content above 90%. These soils generally fall within the USDA textural class of "Sand" (see textural triangle). Studies conducted with variable soil characteristics indicated that all other textural classes will have a lower suitability for culturing SRV clams.

## Your Soil Analysis Results




| Sample ID | No. | Sand % | Silt % | Clay % | OM % |
|---|---|---|---|---|---|
| 1081-a | 1 | 97.8 | 1.2 | 1.0 | 2.0 |
| 1081-b | 2 | 99.5 | 0 | 0.5 | 1.5 |
| 1081-c | 3 | 96.5 | 1.3 | 2.3 | 1.3 |
| | 4 | | | | |
| | 5 | | | | |
| | 6 | | | | |

Results of soil analysis are reported above. Sample ID is the one provided with the sample upon submission. Samples are plotted on an expanded view of the soil textural triangle to the left with red triangle symbols ▲ representing where your samples fall. The green shaded area represents recommended soil conditions for SRV clams, yellow zone represents conditions in which shell deformities begin to increase and are marginally recommended. Unshaded areas are not recommended for SRV culture.

***In the event of questions or concerns, please contact us***

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