MONITORING AND COMPREHENSIVE FINAL PROJECT REPORT 2004-2009

FLOATING MARSH CREATION DEMONSTRATION PROJECT (LA-05)

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Office of Coastal Protection and Restoration

450 Laurel Street, Suite 1200
P.O. Box 44027
Baton Rouge, LA 70804-4027

Submitted by:
LSU Agricultural Center
P.O. Box 25071
Baton Rouge, LA 70894-5071

Charles E. Sasser, Project Director
Professor-Research, LSU Agricultural Center
School of Plant, Environmental and Soil Science

Prepared by:
Charles E. Sasser[1,2], Jenneke M. Visser[2,3], C. Ellery Mayence[4], Mark W. Hester[3,5], Brian J. Milan[2], Joseph Gore[2], Lee Stanton[2],Michael D. Materne[1], and Elaine Evers[2]

[1]LSU Agricultural Center
[2]LSU School of the Coast & Environment
[3]ULL Institute for Coastal Ecology and Engineering
[4]UNO Department of Biological Sciences
[5]ULL Department of Biology

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COMPREHENSIVE SUMMARY

Objective

The objective of this demonstration was to develop methods for restoration of open areas within thin and deteriorated mats that once supported thick-mat maidencane (*Panicum hemitomon*) marsh and other fresh water areas where establishment of maidencane marsh is desired.

The demonstration project consisted of two phases. The first phase, which was performed at Louisiana State University (LSU) and University of New Orleans (UNO), was the development of artificial floating-marsh systems (AFS) and consisted of two components. The first component was development of a floating system which would provide the structure to keep the substrate in place and would provide the buoyancy during the period in which *P. hemitomon* and secondary floating marsh species become established. For this component, structures using a variety of mat materials, support structures, and plant materials were evaluated.

The second component of the first phase consisted of efforts to understand the plant response to nutrients, flooding, and substrate in order to develop methods to maximize the establishment and growth of *P. hemitomon* and secondary species in AFS.

Based on the structural integrity, buoyancy, and growth response results from the first phase investigations, two designs were brought forward for deployment in the second phase. The second phase consisted of field testing of the two selected designs in a marsh setting.

Artificial Floating Marsh Systems Evaluation in Aquaculture Ponds

There were 27 AFS designs developed and tested during the 2004 and 2005 growing seasons at LSU in an outdoor laboratory setting with *P. hemitomon* established from nursery stock and/or plugs harvested from healthy marshes. AFS design dimensions ranged from 1.5-9.3 m^2 (16 to 100 ft^2), with at least three replicates of each. Frames were constructed using pine wood, PVC, Styrofoam, cedar wood, large-diameter bamboo, or combinations of these materials. Mat materials tested included rope, jute netting, straw-coconut, burlap, coconut, birch, as well as hydroponic growth on chicken wire mats. Hardwood mulch and a peat-bagasse mixture were added to several mats to provide additional substrate. Plants were established using plugs harvested from *P. hemitomon*-dominant donor marshes, whole plant fragments (*P. hemitomon* pieces containing both above- and below-ground material), P. *hemitomon* belowground material, or *P. hemitomon* aboveground material. Buoyancy, structural integrity, and plant cover of each AFS were assessed several times a month.

Optimization of Plant Response

A series of greenhouse and controlled-setting experiments were conducted to identify those conditions (i.e., nutrient loading rate, flooding depth, substrate type, mat material, and subordinate plant species) that will not only lead to vigorous growth by *P. hemitomon*, but will facilitate or enhance the overall rate of flotant mat development.

Experiment-1 demonstrated that optimum hydrologic conditions as well as an optimum range of nutrient availability do exist for *P. hemitomon* growth of the type desired for floating marsh creation purposes. An increase in the nitrogen loading rate from 25 to 50 g N m^{-2} yr^{-1} was sufficient to lead to significant increases in both above- and belowground production.

Aboveground biomass was significantly greater under high nitrogen availability, whereas the influence of phosphorous was less evident. Aboveground biomass was significantly greater when subjected to saturated conditions.

Significant differences in *P. hemitomon* growth and vigor were observed across the suite of substrate materials tested in Experiment-2. *P. hemitomon* aboveground production, including total stem number, total stem height, and mean stem height were all greater in the presence of peat or peat-containing substrate materials.

Plant establishment technique exhibited an obvious grouping in regards to *P. hemitomon* vegetative cover. The treatment groups that preformed well included the Duralast coconut fiber alone, or with either canvas underpinning or humic amendment. The poorly-performing treatments included and Duralast coconut fiber with bagasse and chicken wire both alone and with humic acid amendment.

The more species-diverse treatments were not necessarily associated with the greatest proportion of total area vegetated. However, all two-species treatments exhibited greater cover than that exhibited by the *P. hemitomon* only treatment.

P. hemitomon seed production rates were very low, with less than one-tenth of 1% of all florets producing seeds that appeared to be mature and potentially viable. Even if all seeds were considered, including seeds that were clearly non-viable, the percentage is still less than 1%. The unpredictable interannual variation in sexual reproductive effort combined with low seed production rates, even when a greater number of inflorescences are produced, make the use of seeds as an alternative source of plant material of *P. hemitomon* in thick-mat floating marsh creation/restoration projects an untenable option at this time.

Field Testing

Based on the results from phase 1, two structure designs were approved for field testing. The first structure design was a 4 ft x 10 ft PVC Terrace with a wire basket. The second structure design was a 4 ft x 4 ft Bamboo Square with a wire basket. 200 PVC Terrace structures and 100 Bamboo Square structures were deployed at Mandalay NWR in the spring of 2006.

Establishment with potted plants resulted in quicker cover increases than establishment from stems. However by the end of the first growing season, differences in cover between establishment techniques were small, especially in the sites that had the longest growing season.

P. hemitomon cover decreased during the third growing season as the fences that protected it from grazing rusted. However 40 other species colonized and total cover remained high. Tropical storms at the end of the 2008 growing season resulted in decreased cover at the southern sites. All structures remained buoyant and structurally intact in the first two growing seasons. An apparent boat strike near the beginning of the third growing season affected the buoyancy and structural integrity of some of the bamboo structures at site 4, ultimately leading to the sinking of three structures. One string of ten PVC structures vanished from site 1 after Hurricane Gustav, but 81% of the monitored structures and 100% of the unmonitored remained structurally intact after four growing seasons.

FINDINGS

Artificial Floating Marsh Systems Evaluation in Aquaculture Ponds

- Of the 27 structure designs evaluated, only those structures constructed with PVC or bamboo maintained buoyancy.
- *P. hemitomon* cover increased whether established from marsh plugs, whole plants (rhizome and stem material), belowground material, stems, or peat pots. Stems are the most cost effective establishment technique, followed by plants propagated in peat pots.
- Coconut, birch, and coconut-straw mats as well as chicken-wire baskets increased *P. hemitomon* cover. Chicken-wire baskets provide the most cost effective plant material support.

Optimization of Plant Response

- Higher N and P loading rates resulted in:
    - greater aboveground *P. hemitomon* production.
    - greater belowground *P. hemitomon* production.
    - smaller root/shoot ratios (less root allocation per unit of leaf allocation).
    - higher root specific gravity (less buoyant).
- Inundated (15 cm depth) versus saturated (flooded to mat surface (0 cm)) conditions resulted in:
    - decreased aboveground *P. hemitomon* production within the same nutrient loading rate.
    - decreased belowground *P. hemitomon* production within the same nutrient loading rate.
    - higher root specific gravity (less buoyant).
- *P. hemitomon* above- and belowground biomass production exposed to High N loading rates in flooded conditions (inundated) was still greater than the biomass components with low N loading rates in flooded to mat conditions (saturated)
- *P. hemitomon* biomass production was highest on substrates that contained peat.
- *P. hemitomon* biomass production was significantly lower on the birch mat.
- *P. hemitomon* biomass production decreased slightly when planted in combination with other species.
- *Ludwigia peploides* was the only species that displayed potential as a secondary species. It has laterally expanding rhizomes that are aboveground and its roots are sufficiently buoyant.

Field Deployment

- Establishment with plants in peat pots results in quicker cover increases than establishment from stems. However the stem establishment method although slower is the more cost effective establishment technique.
- All structures remained buoyant and structurally intact in the first two growing seasons. Damaged structures and lack of *P. hemitomon* establishment compromised the structural integrity of the bamboo structures at sites 3 and 4. One string of 10 PVC structures disappeared after Hurricane Gustav. Overall performance of the structures was very good during the 3 years of deployment.

- The expansion of vegetative cover both from plantings and natural succession that occurred outside of the direct footprint of the assembled AFS indicates that the field deployment successfully induced formation of a larger mat system.
- The lower *P. hemitomon* performance at sites 3 and 4 may be related to the slightly higher average salinity and occasional salinity spikes exceeding 5 ppt that occur near these sites.

RECOMMENDATIONS

This floating marsh demonstration project was successful in creating conditions in which maidencane (*P. hemitomon*) growth was sustained and productive, developing a viable floating marsh at the Mandalay field site. This developed technology has an excellent potential to create freshwater floating marshes in fresh marsh conditions at the local, basinwide, and coastwide scales. The bullets below highlight the structure and configuration recommended:

- We recommend developing restoration projects to restore shallow open water areas within degraded freshwater marshes, abandoned canals, and other appropriate open water bodies.
    - The artificial floating islands vegetated with *P. hemitomon* can be assembled from modular units to create the appropriate size required for a particular project need.
- We recommend the method tested in this demonstration be used in large and small scale coastal restoration projects.
    - It can be carried out at any scale, depending upon the specific need and funding support available.
- We recommend that this technology be used immediately to develop CWPPRA coastal restoration projects in suitable fresh water marsh areas.
    - The marsh creation technique developed in this demonstration project should be tried at a larger ―project" scale to further determine its success and refine the methods.
- We highly recommend that funding should continue to be solicited for restoration projects to create or enhance floating marshes in degraded freshwater environments using the methods developed in this demonstration project.
- We recommend using bamboo as the first choice in the structures whenever possible because it is a natural, renewable, and biodegradable material.
    - We recommend using 3 inch diameter bamboo poles grouped and bundled together to provide adequate buoyancy for each floating structure.
- We recommend using stem material because the cost is considerably lower. However, stem material needs to be deployed within 24 hours of harvest to avoid desiccation of the stems.
    - Both potted maidencane plants and cut stem material were highly successful as the source material for new plant growth.
    - Potted plants, although more expensive, may survive transportation and storage better.
    - The choice of material is dependent on the logistics of site accessibility.

- Our recommendations from this demonstration project are specific to areas with freshwater conditions and little or no salinity influence throughout the year.
- This technique could potentially be effective in marsh areas influenced by salt water if different plant species suitable for those conditions are used.
- Plant species other than *P. hemitomon*, such as *Ludwigia peploides*,, may be suitable for use in marsh creation and further investigations should be conducted to determine usefulness of appropriate plant species .

Specific Recommendations

- We recommend using dimensions of 4ft by 8ft for the artificial floating structures, although other dimensions could easily be used as well. Time required to assemble a single structure is approximately 1 hour. These dimensions provide
    - adequate area for plant production,
    - are a reasonable size structure to deploy, and
    - efficiency in use of construction materials.
- We recommend that nutria control be accomplished through trapping and hunting techniques, or an extension of the CWPPRA nutria control program.
- We recommend that the configuration of floating structures deployed at a marsh creation site be designed to fit the particular attributes of that site.
    - Our general recommendation is to use a single row comprising a set of 3 linear rows of structures.
    - As many additional rows as funding allows within the open water areas to create new marsh could be incorporated into the design.
    - We also recommend a double row, which allows more stability in open water areas.
- Based on the results of the demonstration project and subsequent experience we recommend late winter/early spring (March/April) as the best months of the year to deploy vegetated floating structures in marsh sites needing restoration.

Expectations

- Our expectation is that the floating structures will develop a viable vegetation mat with productive plants that will provide a sustainable floating mat.
- We expect that a project implemented in a freshwater area using the techniques developed in this demonstration project will be effective in establishing new freshwater marsh in open water areas associated with degraded freshwater marsh in coastal Louisiana.
- Maintenance costs should be low, providing the floating structures are not impacted and damaged by tropical storms, boat strikes, etc.
- We estimate that < 10% (30 out of 300 structures) of the demonstration project materials were damaged over the 4 year period of deployment, and we expect that components of future projects using this technique would have a similar response to environmental conditions over the 20 year period of the restoration project.

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INTRODUCTION

The Coastal Wetlands Planning, Protection, and Restoration Act (CWPPRA) of 28 November, 1990, House Document 646, 101st Congress, provides for the use of federal funds for planning and implementing projects that create, protect, restore, and enhance coastal wetlands of the United States, including Louisiana. The Floating Marsh Creation Demonstration Project (LA-05) was approved for funding and included on the Twelfth Priority Project List which was transmitted to Congress in December 2003.

Land loss in coastal Louisiana has been well documented and linked to a variety of causes (Craig et al. 1979, Gagliano et al. 1981, Sasser et al. 1986, Evers et al. 1992, Britsch and Dunbar 1993). This 90 km^2 yr^{-1} (20,000 acres yr^{-1}) loss covers all marsh types, including freshwater floating marshes. Even though the remaining marshes in the upper part of the coast have remained fresh since they were first mapped by O'Neil (1949), significant areas of marsh have converted to open water, and vegetation associations have changed from thick-mat maidencane (*Panicum hemitomon*) dominated marsh to thin-mat spikerush (*Eleocharis baldwinii*) dominated marsh (Visser et al. 1999). Visser et al. (1999) identified the following potential causes for the dramatic change in fresh marsh vegetation and land loss: grazing by nutria, increased water levels, hydrologic modifications, and eutrophication. Increased salinity and sulfide concentrations as a result of hydrologic alterations have also been identified as a stressor on *P. hemitomon* marshes (Gosselink and Sasser 1995). Sasser et al. (2005) showed that grazing by nutria may be the most important of these factors in freshwater marshes. Although the effect of nutria grazing on maidencane marshes has not yet been directly quantified, nutria grazing helps prevent the re-establishment of *P. hemitomon* in spikerush marshes (Visser et al. 2001). In addition, recent research has shown that *P. hemitomon* grows well in the spikerush floating marsh with or without nutrient enhancement when protected from grazing (Sasser et al. 2005). This indicates that no nutrient limitation exists in the maidencane marsh areas that have converted to spikerush marsh and open water.

The belowground structure of *P. hemitomon* is characterized by extensive root and rhizome allocation that results in an organic root mat that is very fibrous and buoyant. *P. hemitomon*'s extensive network of fibrous roots and rhizomes is crucial for forming well-integrated floating marsh mats. The ability of other co-dominant or subordinate species (e.g., *Sagittaria lancifolia*, *E. baldwinii*) to form this type of highly-buoyant floating root mat in the absence of *P. hemitomon* seems improbable based on their respective belowground morphologies and general architecture. Therefore, *P. hemitomon* probably plays a key role in the successful formation and sustainability of healthy (thick mat) freshwater floating marshes (Sasser et al. 1994, Holm et al. 2000), and is the primary plant species utilized in this project.

Wetland plant species typically display aerenchyma (tissue air space) development in their tissues, which facilitates oxygen diffusion to the roots and may also reduce the amount of living, respiring tissue in roots relative to root volume (Armstrong 1979, Jackson et al. 1985, Schussler and Longstreth 1996). Although wetland plants generally form aerenchymatous tissues during their normal development, aerenchyma can also be induced in many wetland plants when subjected to waterlogged or hypoxic conditions (Schat 1984, Burdick 1989, Schussler and

Longstreth 1996). Formation of adventitious roots is widespread in grass species regardless of soil conditions, but also occurs in plants subjected to conditions in which the primary root cannot function properly, such as in waterlogged conditions where soil oxygen levels are depleted to the point of inhibiting aerobic metabolism (Jackson and Drew 1984). Flood-induced adventitious roots are typically very porous due to the prevalence of aerenchymatous tissue, which facilitates the diffusion of gases, such as oxygen from shoots to roots, thereby enabling many plants to grow in hypoxic or anoxic soils (reduced soils) that typically form under flooded conditions (Armstrong 1979, Dacey 1980, Jackson et al. 1985; Drew 1992; Naidoo et al. 1992). Therefore, the induction of aerenchyma and the formation of adventitious roots are viewed as mechanisms of facilitating aerobic root respiration under flooded soil conditions and would likely have tremendous implication for root production and mat buoyancy in floating marshes.

Project Objective

In this report, we present comprehensive results of the Floating Marsh Creation Demonstration Project (**LA-05)**. The objective of this demonstration was to develop methods for restoration of open areas within thin and deteriorated mats that once supported thick-mat maidencane marsh (dominated by *P. hemitomon*) and other fresh water areas where establishment of maidencane marsh is desired.

The demonstration project consisted of two phases. The first phase was performed at Louisiana State University (LSU) and University of New Orleans (UNO) between summer 2004 and the end of the 2005 growing season. This phase included the development of artificial floating-marsh systems (AFS) and consists of two components. The first component was development of a floating system which would provide the structure to keep the substrate in place and would provide the buoyancy during the period in which *P. hemitomon* and secondary floating marsh species become established. For this component, structures using a variety of mat materials, support structures, and plant materials were evaluated. The second component of the first phase consisted of efforts to understand the plant response to nutrients, flooding, and substrate in order to develop methods to maximize the establishment and growth of *P. hemitomon* and secondary species in AFS.

Based on the structural integrity, buoyancy, and growth response results from the first phase investigations, two designs were brought forward for deployment in the second phase. The second phase consisted of field testing the two designs in a marsh setting, and was initiated in March 2006.

METHODS

Artificial Floating Marsh Systems (AFS)

Illustration 1. Testing of Artificial Floating Marsh Systems (August 22, 2005).

Twenty-seven ASF designs were developed and tested from July 2004 through October 2005 at LSU in an outdoor laboratory setting with *P. hemitomon* established from nursery stock and/or plugs harvested from healthy marshes (Appendix A). ASF design dimensions ranged from 1.5-9.3 m^2 (16 to 100 ft^2), with at least three replicates of each. Frames were constructed using pine wood, PVC, Styrofoam, cedar wood, large-diameter bamboo, or combinations of these materials (Table 1). Mat materials tested included rope, jute netting, straw-coconut, burlap, coconut, birch, as well as hydroponic growth on chicken wire mats. Hardwood mulch and a peat-bagasse mixture were added to several mats to provide additional substrate. Plants were established using plugs harvested from *P. hemitomon*-dominant donor marshes, whole plant fragments (*P. hemitomon* pieces containing both above- and below-ground material), *P. hemitomon* belowground material, or *P. hemitomon* aboveground material (Table 1).

Construction was designed such that each AFS could be assembled in the field. Each design incorporated an anchoring system to minimize horizontal movement, while not hindering vertical movement of the AFS, using biodegradable materials where feasible. The AFSs were designed to maintain sufficient structural integrity and buoyancy until the established *P. hemitomon* mat becomes self-sustainable. The fabrication of each design was such that multiple units can be attached one to another to create larger areas of floating *P. hemitomon* marsh for field testing. Structures of AFS 1 through 12 were deployed in the LSU ponds in the summer of 2004, structures of AFS 13 through 24 were deployed in the spring of 2005, and structures of AFS 25 through 27 were deployed in summer 2005. Fences were added to structures of AFS 5, 6, 7, and 12 in October 2004 to eliminate grazing. In March 2005, the previously fenced structures were replanted and AFS 3 was replanted and fenced. Structures of AFS 15 through 27 were fenced before deployment in the pond. Buoyancy, structural integrity, and plant cover of each AFS were assessed several times a month.

Table 1. Overview of the 27 Artificial Floating Systems developed during 2004-05.

AFS	Dimension (ft)	Frame	Mat	Substrate	Plant Source
1	10 x 10	pine	rope	none	large plugs
2	10 x 10	pine	jute	hardwood mulch	plugs
3	4 x 10	PVC & pine	straw-coconut	hardwood mulch	plugs
4	10 x 10	Styrofoam & pine	burlap	hardwood mulch	plugs
5	10 x 10	PVC	coconut	hardwood mulch	A & C plugs; B whole plants
6	4 x 4	pine	birch	hardwood mulch	plugs
7	4 x 4	PVC	coconut	hardwood mulch	plugs
8	4 x 4	none	burlap	water-hyacinth	plugs
9	4 x 4	pine & Styrofoam	coconut	hardwood mulch	plugs
10	4 x 4	pine	coconut	hardwood mulch	plugs
11	4 x 4	pine	rope	none	plugs
12	4 x 4	pine	chicken-wire	none	plugs
13	4 x 4	PVC	chicken-wire	none	plugs
14	4 x 4	PVC	chicken-wire	peat & bagasse	whole plants
15	4 x 4	cedar lattice	coconut	none	plugs
16	4 x 4	cedar lattice	coconut	none	plugs
17	4 x 4	cedar lattice	none	none	plugs
18	4 x 4	cedar lattice	coconut	none	plugs
19	4 x 4	pine	chicken-wire	none	A & C whole plants; B plugs
20	4 x 4	pine	birch	peat & bagasse	A & B plugs; C whole plants
21	4 x 4	pine	coconut	peat & bagasse	A & B plugs; C whole plants
22	4 x 4	bamboo	chicken-wire	none	A whole plants; B & C plugs; D, E, & F belowground; G, H, I aboveground
23	4 x 4	bamboo	birch	peat & bagasse	B & C whole plants; A plugs
24	4 x 4	bamboo	coconut	peat & bagasse	A & B whole plants; C plugs; D, E, & F belowground; G, H, I aboveground
25	4 x 4	PVC	none	styrofoam	peat pots
26	4 x 10	PVC	chicken-wire	peat	peat pots
27	4 x 10	PVC	chicken-wire	none	whole plants

Plant establishment

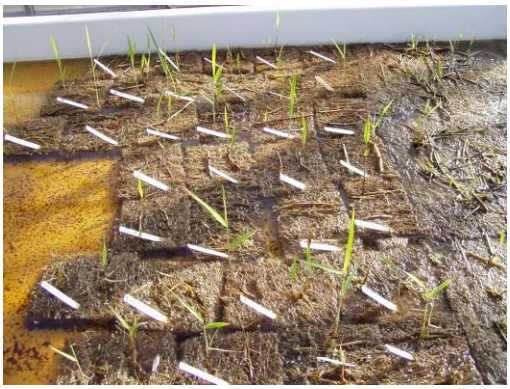

Illustration 2. Testing of Vegetative Establishment

Along with establishing AFSs, a source for harvesting the plants needed to be developed. Therefore, types of plant material that could be used to establish *P. hemitomon* were tested under greenhouse conditions. The applications of using *P. hemitomon* whole plants, as well as rhizome or aerial stem material, were tested. Furthermore, tests were conducted to determine the smallest segment of the rhizomes and aerial stems needed to consistently produce new plants. Plant segments tested included no node, one node, and two node pieces. The testing was conducted by placing fragment, stem and rhizome pieces on individual squares of coconut mat material. These mats were monitored to determine the number of shoots produced by each different type and size of plant material.

Optimization of Plant Response

A series of greenhouse and controlled-setting experiments were conducted in an effort to elucidate growth characteristics and patterns of biomass allocation in *P. hemitomon*. More specifically, it was our intent to identify those conditions (i.e., nutrient loading rate, flooding depth, substrate type, mat material, and subordinate plant species) that would not only lead to vigorous growth by *P. hemitomon*, but would facilitate or enhance the overall rate of flotant mat development within the restoration context. These experiments are described in more detail below.

Experiment-1: Evaluating the effects of nutrient loading rate and flooding depth

Illustration 3. Experiment-1.v1 (before Katrina): Evaluating the effects of nutrient loading rate and flooding depth

The first version of this experiment (Experiment - 1.v1) was initiated in June of 2004 and ended prematurely in August of 2005 as a result of extensive flooding and physical damage associated with Hurricane Katrina. The experimental design was a 3 x 3 x 2 completely cross-classified factorial with 3 levels each of both nitrogen and phosphorous and 2 levels of flooding, all replicated in 5 blocks for a total of 90 experimental units (n = 90). Nitrogen was applied at the rates of 2.5, 25, and 50 g N m^{-2} yr^{-1} and phosphorous was applied at a the rates of 0.5, 5, and 10 g P m^{-2} yr^{-1}. Additions of N and P were administered weekly while micronutrient solutions were applied monthly, coinciding with the monthly rinsing and scrubbing of the vessels.

Illustration 4. Experiment-1.v1: Destruction due to Hurricane Katrina

Nutrient solutions were completely replaced to minimize algal growth. Flooding treatments were flooded to the surface of the mat (flooding depth of 0 cm, (~~"s~~aturated")) and flooded to a depth of 15 cm (~~"i~~nundated-15 cm"). Each experimental unit consisted of two square layers of DuraLast coconut fiber mat (Duralast Products, Memphis, TN) fastened together by plastic tie straps. This was essentially a hydroponic design that did not include a typical substrate material (i.e., the DuraLast coconut fiber served as the planting medium and substrate). Four individual plugs of commercially-grown *P. hemitomon* were planted into the corners of each double-layer mat sandwich, and each vegetated mat was placed in their respective experimental units. Each vessel was filled to near-capacity with deionized water to ensure that manipulations of nutrient availability remained constant. Flooding treatments (saturated and inundated-15 cm) were maintained by placing each vegetated mat on a segment of 4" diameter PVC pipe that was cut to a pre-determined length.

Data collection included bi-weekly (initially) and then monthly measurements of cumulative stem height. Maximum root length and percent root coverage were measured and/or estimated bi-monthly, although these assessments did not occur until several months after the initiation of the experiment. Maximum root length represented the distance from the bottom of the vegetated mat to the tip of the longest root, while percent root coverage represented the percentage of area of the bottom of the vegetated mat with root tissue protruding from it. Net photosynthesis and stomatal conductance were measured at peak standing crop (after 12 months of growth) using a Li-Cor 6400 portable photosystem. Net photosynthesis and stomatal conductance were measured on a single leaf, second from the terminal leaf of each plant in each experimental unit. Each leaf was then clipped, dried and ground for CHN analysis. Root specific gravity was measured in June of 2005. Live root samples were clipped from each vegetated mat and taken to the Coastal Plant Sciences Laboratory for analysis. Root specific gravity was computed using the formula: $SG = R/ (P + R - PR)$, where R = mass of roots, P = mass of water-filled pycnometer, and PR = mass of pycnometer with roots and water. Biomass was measured on 62 of the 90 experimental units post-Katrina. The remaining 28 units were not identifiable, and consequently not recoverable. Separating biomass into live and dead was not possible because the majority of the vegetated mats succumbed to desiccation stress. Biomass was therefore divided into dead above- and belowground. All biomass was oven-dried at 60˚C until a constant mass was attained.

Experiment-1.v2 initiated after Katrina in March of 2006 was designed much like the first version in terms of the experimental design and the expected outcomes. The experimental design was a 2 x 2 x 2 completely cross-classified factorial with 2 levels of both N and P loading, and two levels of flooding, replicated in 5 blocks for a total of 40 experimental units (n = 40). The two nitrogen loading rates were 25 and 50 g N m^{-2} yr^{-1} and phosphorous loading rates were 5 and

Illustration 5. Experiment-1.v2 (after Katrina): Evaluating the effects of nutrient loading rate and flooding depth.

10 g P m^{-2} yr^{-1}. As in the first version, flooding depths were either saturated or inundated-15. The primary difference between the experiment before and after Katrina was the addition of a true substrate to the double-layer DuraLast coconut fiber configuration. Sphagnum peat served as the substrate and was placed between the two layers of coconut fiber. Plastic tie straps were once again used to fasten the materials together. A single plug of *P. hemitomon* was planted in the center of each DuraLast coconut fiber and peat sandwich. Plant material for Experiment-1.v2 (post-Katrina) was collected from a non-cultivated population of *P. hemitomon* on the USDA Golden Meadow Plant Materials Center property in Galliano, LA. Root stock was brought back to the UNO greenhouse facility and propagated until planting occurred.

Data collection followed a similar protocol as before Katrina, although several modifications were made to the sampling regime. Cumulative stem height was measured monthly over the 4 month course of the experiment. In an effort to minimize disturbance of each experimental unit, maximum root length and percent root coverage were not measured. On the other hand, substrate redox potential was measured bi-monthly. As in the first version, root specific gravity was assessed at peak standing crop (June 2006), as was net CO_2 assimilation and stomatal conductance. Leaf samples were clipped, dried and ground for CHN analysis. Additional leaf material was collected for determining the relationship between leaf mass and leaf area. The most significant changes in the methods for Experiment-1.v2 occurred at harvest. Each vegetated mat underwent a complete census which not only included the separation of biomass into above- and belowground components, but the separation of belowground biomass into roots and rhizomes. Each vegetated mat was disassembled and all biomass recovered. Aboveground biomass was clipped, All material was live at the time of harvest. The length of all rhizomes was measured, and all root tissue was set aside for further analyses. Complete root systems were scanned and quantified in terms of volume using an Epson 10000XL high-resolution scanner and Whin-Rhizo Pro-Version root imaging software (Regent Instruments, Quebec, Canada). Furthermore, 5 individual root samples from each root system were reserved in order to assess individual root morphology, once again using Whin-Rhizo Pro-version root imaging software. All above- and belowground biomass was oven-dried at 60˚C until a constant mass was attained.

Experiment-2: Evaluating the effects of substrate type

Experiment-2.v1 was initiated in October of 2004 and ended prematurely in August of 2005 due to Hurricane Katrina. In preparation for the eminent landfall of Hurricane Katrina this experiment was relocated from an outdoor setting to a semi-protected greenhouse setting where it was spared physical damage (although all plant material subsequently died due to desiccation because the UNO Campus was inaccessible for over one month post-Katrina).

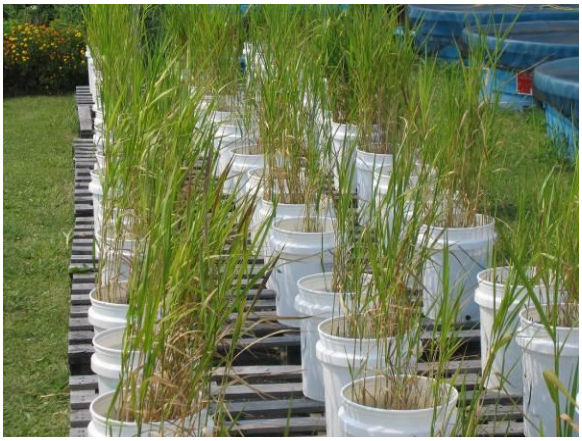

Illustration 6. Experiment-2.v1: Evaluating the effects of substrate type.

The experimental design included one mat material (DuraLast coconut fiber), multiple substrate types (7 individual types and 5 blends), all replicated in 5 blocks for a total of 60 experimental units (n = 60). Each experimental vessel contained a layer of mat material followed by a layer of substrate, culminating with another layer of mat material in that order from bottom to top. Individual substrate types included sphagnum peat, bagasse, sugarcane leaf strippings, pine shavings, cypress mulch, hardwood mulch, and pine bark mulch. Substrate blends included sphagnum peat x bagasse, sphagnum peat x hardwood mulch, sphagnum peat x cypress mulch, cypress mulch x bagasse, and hardwood mulch x sugarcane leaf strippings. The fertilization regime, applied once every three months, was uniform across all treatments (23.4 g N m^{-2} yr^{-1} and 2.0 g P m^{-2} yr^{-1}). Flooded conditions were maintained at 10 cm above the mat's surface (inundated-10) in all treatments. A single plug of *P. hemitomon* was planted in the center of each DuraLast coconut fiber and substrate sandwich. Plant material was collected from a non-cultivated population of *P. hemitomon* on the USDA Golden Meadow Plant Materials Center property in Galliano, LA. Root stock was brought back to the UNO greenhouse facility and propagated until planting occurred.

Cumulative stem height was measured monthly over the duration of the experiment, while interstitial metrics such as pH, conductivity and substrate redox potential were measured bi-monthly. Net carbon dioxide (CO_2) assimilation and stomatal conductance were measured on a single leaf, second from the terminal leaf of each plant in each experimental unit. These measurements were done using a Li-Cor 6400 portable photosystem. Each leaf was clipped, dried and ground for CHN analysis. Because all experimental units were not living at the time of salvage, harvest followed a different protocol than was originally intended. Above- and belowground biomass was separated but root and rhizome components were not distinguishable, nor were they separable from the substrate itself. Because of this, all belowground biomass had to be described in terms of a total change value. Pre-weights were determined at the outset of the experiment, and when combined with dry weights at the time of harvest, allowed for the calculation of a total change value. All biomass was oven-dried at 60˚C until a constant mass was attained.

Illustration 7. Experiment-2a v.2: Evaluating the chemical oxygen demand of each substrate type.

Experiment-2.v.2 was designed to elucidate substrate chemical oxygen demand (COD) as a function of substrate type and was conducted between February 2006 and September 2006. The original 7 individual substrates, along with two controls (water only and water x DuraLast coconut fiber) served as the 9 treatments. Each treatment

was replicated 5 times for a total of 45 experimental units (n = 45). Interstitial samples were withdrawn throughout the study and sent to Nichols State University in Thibodaux, LA for processing and analysis. Interstitial pH was measured at each sampling, and substrate redox potential was measured twice over the 20-week period. Pre-weights were determined for all experimental units at the outset of the experiment, and final weights were determined at completion. This allowed for the calculation of substrate mass loss due to decomposition.

Experiment-3: Evaluating the effects of mat type on vegetation establishment

Illustration 8. Experiment-3: Evaluating the effects of mat type.

Experiment-3.v1 was initiated in May of 2005 and, like Experiment-2.v1, ended prematurely in August of 2005 due to Hurricane Katrina. Experiment-3.v1 was also relocated from an exposed outdoor setting to a semi-protected greenhouse setting where it was spared physical damage (but as with Experiment-2.v1, all plant material died due to desiccation stress). The overall objective of this experiment was not only to compliment the results of the substrate experiment (Experiment-2), but to specifically assess *P. hemitomon* growth responses when grown in conjunction with different commercially available mat or containment materials.

The experimental design for Experiment-3.v1 included 5 mat materials and 1 substrate material (sphagnum peat), all replicated 5 times for a total of 25 experimental units (n = 25). Mat materials included two composed of coconut fiber (i.e., DuraLast coconut fiber and plain coconut fiber with plastic mesh) and one each of burlap, shredded birch and wheat straw. Each sphagnum peat and mat combination was housed in a 7.5-L container and flooded to a depth of approximately 10 cm above the surface of the mat (~~"i~~nundated 10 cm"). Fertilizer, applied once every three months, equaled 23.4 g N m^{-2} yr^{-1} and 2.0 g P m^{-2} yr^{-1}. A single plug of *P. hemitomon* was planted in the center of each mat and sphagnum peat sandwich. Plant material was collected from a non-cultivated population of *P. hemitomon* on the USDA Golden Meadow Plant Materials Center property in Galliano, LA. Root stock was brought back to the UNO greenhouse facility and propagated until planting occurred.

Cumulative stem height was measured monthly over the course of the experiment, while interstitial pH and substrate redox potential were measured bi-monthly. Similar to that of Experiment-2.v1, harvest of this experiment did not proceed as planned due to Hurricane Katrina. All biomass was dead and therefore only separable into dead above- and belowground components. Above- and belowground biomass was separated but root and rhizome components were not distinguishable, nor where they separable from the substrate itself. All biomass was oven-dried at 60˚C until a constant mass was attained.

A second experiment (Experiment-3.v2) evaluating an additional set of support structures was initiated in April of 2006 and completed after 5 months of growth in September 2006. The experimental design involved five treatments, each replicated four times in a completely

randomized fashion for a total of 20 experimental units (n = 20). The five treatments (including their abbreviation) were as follows: peat and Duralast coconut fiber with humic acid amendment (PDH), bagasse and Duralast coconut fiber (PDB), chicken wire (PC), chicken wire with humic acid amendment (PCH), and peat and Duralast coconut fiber with canvas underpinning (PDC). All five treatments regardless of species combination or plant establishment technique received nine bare-root plugs of *P. hemitomon* planted in a 3 x 3 arrangement. Plugs were approximately two months old at planting. In an effort to avoid biased results, care was taken to ensure that initial *P. hemitomon* masses were uniform across all treatments. All *P. hemitomon* plant material used in this experiment was harvested from a single clone growing at the USDA Golden Meadow Plant Materials Center, Galliano, LA. Root stock was transported back to the University of New Orleans and propagated under optimum conditions until planting occurred.

All treatments were maintained in a fully-exposed outdoor setting at the University of New Orleans. Experimental vessels were 1330 L (2.6 m^2 surface area equivalent) livestock watering tanks filled to capacity with a combination of tap and rain water (both tap and rainwater for the first two months and exclusively rainwater for the final three months). Buoyancy for all treatments was achieved by way of a rectangular support structure fashioned from 3.8 cm diameter PVC (polyvinylchloride) pipe. Each created mat (chicken wire treatments excluded) was supported within the flotation device by a cross-hatching of nylon rope. The fertilization regime was the same as with all experiments described above. The humic acid amendment, 3.0% active ingredient Actisol (Arctec Inc, Little Rock, AR), was applied as a foliar spray on the first of each month over the 5-month duration of the experiment at a rate of 4 ml m^{-2} mo^{-1}.

Data collection included monthly aerial photographs of each experimental unit in order to assess vegetative spread of each mat. This was accomplished by constructing a large tripod that rested on the rim of each tank. An infra-red remote shutter release was used to ensure a clear photograph of each tank was obtained. Each digital picture was overlain by a grid of known size in order to determine plant species cover.

At harvest each mat was removed from its tank and support structure and completely dissembled much like Experiment-1.v2. *P. hemitomon* aboveground biomass was separated from belowground biomass, which was further partitioned into roots and rhizomes. All belowground biomass was hand-picked from both the top and bottom layers of each mat. Moreover, in those treatments that contained substrate (i.e., non-chicken wire treatments), all substrate was washed and fine root tissue removed. The length of each rhizome segment was measured to estimate a total rhizome length per mat. In this way total rhizome length provided a metric for inferring the lateral spreading potential of *P. hemitomon* within each treatment. All biomass, regardless of species, was oven-dried at 60˚C until a constant mass was attained.

Experiment-4: Evaluation of edge-expansion species

Illustration 9. Experiment-4: Evaluating the effects of mat expansion species.

Experiment-4.v1 was designed to incorporate aspects of previous experiments, along with an evaluation of additional plant ("edge") species. This experiment also allowed for the elucidation of inter-specific competition among common thick-mat plant species.

Experiment-4.v1 was initiated in July of 2005 at an off-campus site owned and managed by the University of New Orleans. After a brief acclimation period, and before data collection could begin, this experiment was totally destroyed in August of 2005 by flooding and storm surge associated with Hurricane Katrina. Because of the severity of the impact and the early termination of the study, no further details are provided.

Experiment-4.v1 was replaced in March of 2006 by Experiment-4.v2 and was completed in September of 2006. It was conducted in an outdoor setting within the greenhouse complex at the University of New Orleans. The experimental design included 7 plant combinations, each replicated 4 times for a total of 28 experimental units (n=28). The 7 plant combinations included: *P. hemitomon* only, *P. hemitomon* x *Alternanthera philoxeroides* (alligator weed), *P. hemitomon* x *Hydrocotyle ranunculoides* (floating pennywort), *P. hemitomon* x *Ludwigia peploides* (floating swamp primrose), *P. hemitomon* x *Sagittaria lancifolia* (bull tongue), *P. hemitomon* x all edge species (excluding *S. lancifolia*), and *P. hemitomon* x all plant species (including *S. lancifolia*). Each treatment received 9 plugs of *P. hemitomon* planted in a 3 x 3 grid fashion. *P. hemitomon* plant material for Experiment-4 was also harvested from the USDA Golden Meadow Plant Materials Center property in Galliano, LA. Root stock was brought back to the UNO greenhouse facility and propagated until planting occurred. All other species were wild-harvested from various road-side wetlands in Orleans, Lafourche, Jefferson, or St. John the Baptist Parishes. Moreover, none of the non-*P. hemitomon* species were propagated, but were gathered and planted within a 48 hour period. In all plant combinations that contained substrate DuraLast coconut fiber served as the mat material and sphagnum peat served as the substrate material.

Illustration 10. Experiment-4: Example of aerial photograph.

Data collection included monthly aerial photographs of each experimental unit in order to assess vegetative spread of each mat, as well as to estimate percent cover by species in the multi-species treatments. This was accomplished by constructing a large tripod that rested on the rim of each tank. An infra-red remote shutter release was used to ensure a clear photograph of each tank was obtained. Each digital picture was overlain by a grid of known size in order to determine plant species cover.

At harvest each mat was removed from its tank and support structure and completely dissembled much like Experiment-1.v2 after Hurricane Katrina. *P. hemitomon* aboveground biomass was separated from belowground biomass, which was further partitioned into roots and rhizomes. All belowground biomass was hand-picked from both the top and bottom layers of each mat. Moreover, in those treatments that contained substrate (i.e., non-chicken wire treatments), all substrate was washed and fine root tissue removed. The length of each rhizome segment was measured to estimate a total rhizome length per mat. In this way total rhizome length provided a metric for inferring the lateral spreading potential of *P. hemitomon* within each treatment. In multi-species treatments, all biomass was separated by species, including both above-and belowground components. However, above- and belowground biomass are reported together as total biomass for the species other than *P. hemitomon*. Live root samples, 5 per treatment, were taken from each species in order to determine root specific gravity. Root specific gravity was determined using the same formula as described in Experiment-1.v1. All biomass, regardless of species, was oven-dried at 60˚C until a constant mass was attained.

Experiment-5: Evaluation of P. hemitomon seed production and germination potential.

Illustration 11. Experiment-5: Dr. Hester collecting P. hemitomon inflorescences.

Annual observations were conducted each spring during this project period (2004–2007) for any visible signs of *P. hemitomon* flowering activity (i.e., production of inflorescences or flowering stems) in south Louisiana. Observations were made in areas of known populations that could be accessed by automobile (such as along LA HWY 90 corridor in the vicinity of Des Allemands to Houma), as well as through contact with other researchers in the field, managers at wildlife refuges, and personnel at the NRCS Plant Materials Center in Galiano, Louisiana. In the late spring of 2007, the *P. hemitomo*n in the AFSs were found to be flowering. During the May 2007 sampling of these structures, ocular counts of all flowering stems (inflorescences) were made. Counts were recorded by the type of structure and type of planting unit deployed. At each of the four field deployment locations, subsamples of inflorescences were collected (65 inflorescences total), bagged and labeled, and transported to the lab for analysis.

Once at the lab, inflorescences were kept in open bags at room temperature. For each inflorescence, the total number of florets (flowers that could potentially produce a seed) was counted. Inflorescences from each site were then pooled and repeatedly mechanically agitated to dislodge any seeds from inside the florets (see Hester and Mendelssohn 1987). Any seeds that were identified were further examined under magnification for degree of development. The average number of seeds produced per inflorescence was calculated, as was the average number of florets per inflorescence and the average number of inflorescences per area of created floating marsh by treatment type.

Statistical Analyses

All analyses were performed using SAS statistical software, version 9.1 (SAS Institute Inc., Cary, NC). In most cases either a one or two-way ANOVA was used to test for differences in particular variables. When specific variables were measured multiple times over the course of a given experiment (i.e., cumulative stem height), a repeated measures ANOVA was used. All variables were evaluated independently to ensure that each clearly met the normality and heteroscedasticity assumptions. Statistical significance was set at an alpha level of 0.05 unless specified otherwise. For tests of significance associated with MANOVA outputs, preference was given to Wilk's lambda when test of significance values did not differ. When differences did exist, preference was given to Pillai's trace because of its robustness to violations of assumptions (Kleinbaum et al. 1998; Scheiner and Gurevitch 2001).

Field Deployment

Mandalay National Wildlife Refuge (MNWR) in Terrebonne Parish Louisiana was selected as the location for field deployment. MNWR is located within the historical area that once supported a large expanse of thick-mat floating maidencane marsh that in recent decades has undergone extensive conversion to open water and/or thin-mat floating marsh. The U.S. Fish and Wildlife Service has issued a Special Use Permit for full implementation of the project. MNWR utilizes trappers supported by the Coastwide Nutria Control Program to control nutria.

Within MNWR, four deployment sites were identified (Figure 1). Two deployment sites are in large open water bodies, and two deployment sites are in small open water bodies. Sites 2 and 4 are located in a large open water area and are open to wind fetch. Sites 1 and 3 are in small ponds and are protected from wind fetch in most directions. The small open water bodies are small enough that the deployed structures occupy greater than 50% of the available space. After deployment it became evident that the pond at site 1 varies in size due to the movement of the thin-mat marsh that surrounds it, while still remaining a small pond. In contrast, the pond at site 3 maintains its shape because the surrounding marsh is an attached marsh dominated by *S. lancifolia*.

Based on the structural integrity, buoyancy, and growth response results from the first phase investigations, two successful AFS designs (see results section) were selected for field deployment in a marsh setting. The first design uses PVC for buoyancy and is based on AFS 26 (Table 1, Appendix A). The AFS 26 design was modified by adding two additional spacers in between the PVC tubes (Figure 2). This improved PVC design was repeated 50 times at each deployment site (Figure 3) for a total of 200 structures. The second design uses bamboo for buoyancy and is the same as the AFS 22 design (Table 1, Appendix A; Figure 2). This bamboo design was repeated 25 times at each deployment site (Figure 3) for a total of 100 structures. Only 25 bamboo structures were constructed per site due to budget and time constraints.

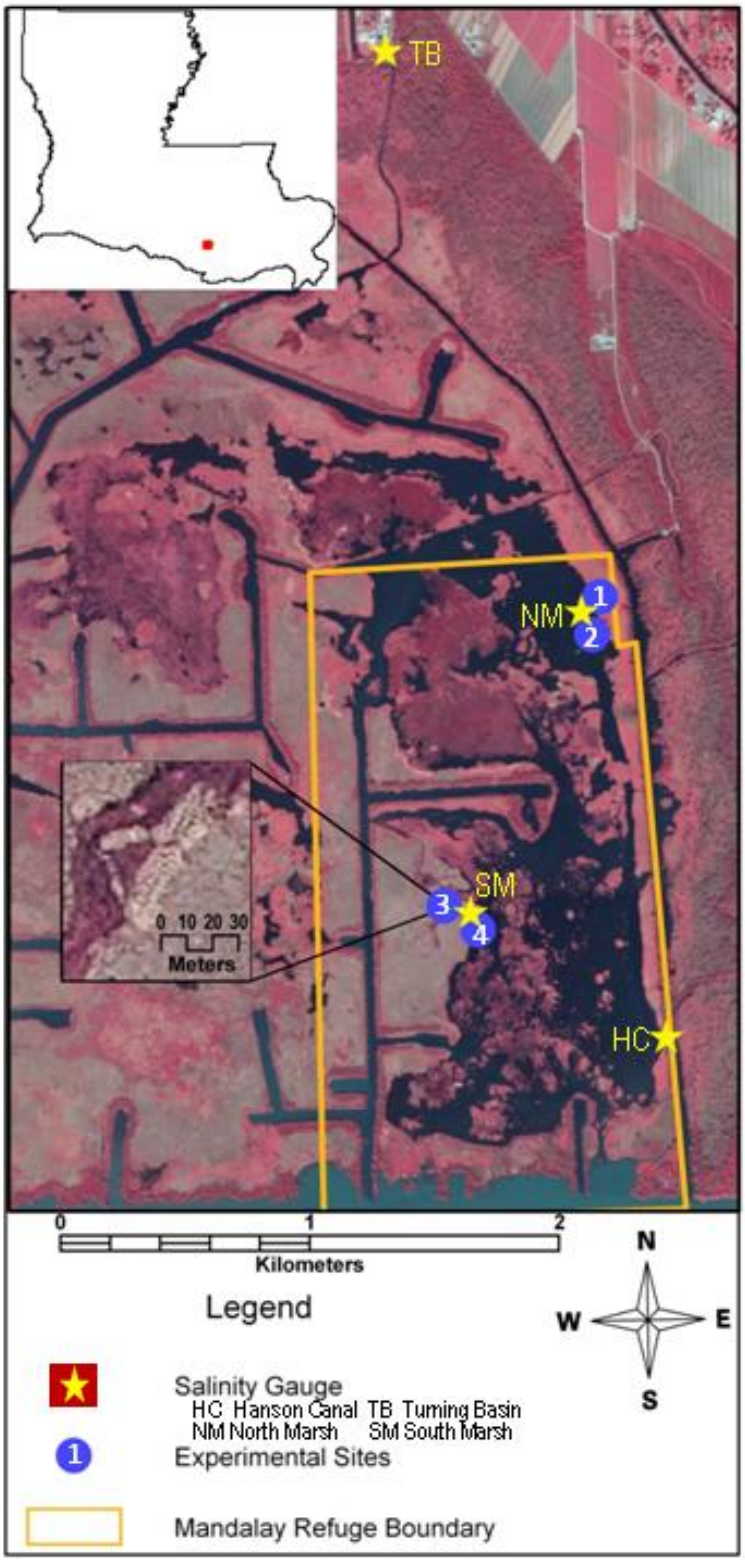

Figure 1. Location of sites within Mandalay National Wildlife Refuge (MNWR).

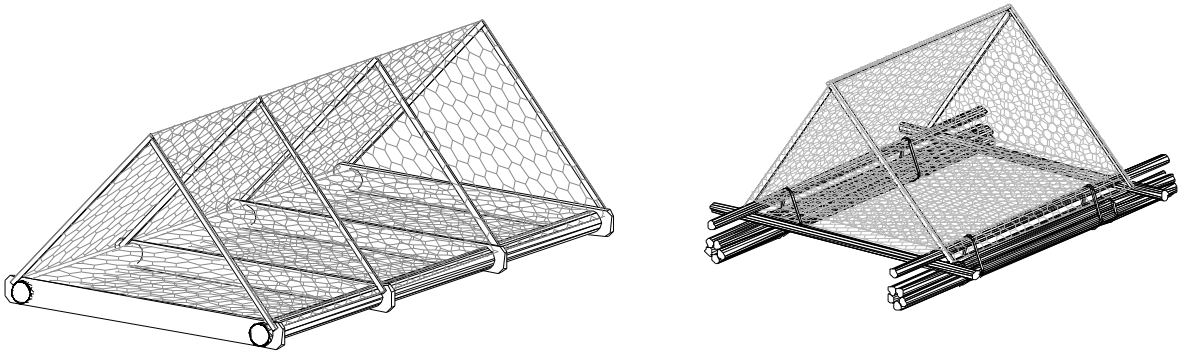

Figure 2. Structure designs deployed in the field, showing PVC structure on left and bamboo structure on right.

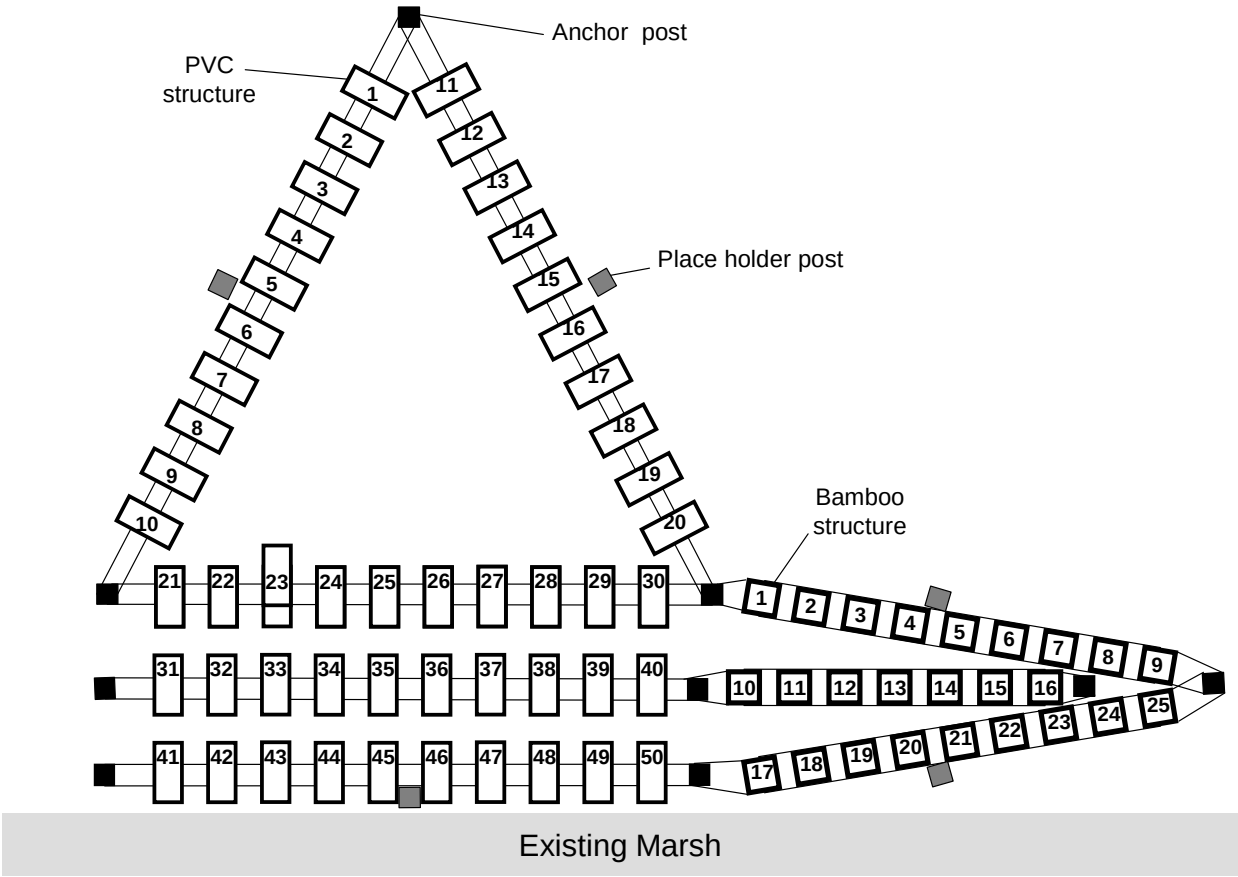

Figure 3. General layout of structures at each site. Drawing is not to scale.

Layout of the structures (Figure 3) at each site included different spacing between structures. For the PVC structures, 30 structures were arranged in a relatively tight grid (~4 ft spacing) to promote rapid coalescence of structures into a mat. The additional 20 structures were arranged into a triangle, with the expectation that the triangle would trap free floating vegetation (e.g. *Eichhornia crassipes*) and initiate natural mat formation inside the triangle. This arrangement maximizes the extent of mat formation with minimal structure investment. The potential drawback of the open triangle arrangement is higher exposure of all structures to wave action. The bamboo structure design is an intermediate arrangement of the two PVC layouts.

Structure construction started at LSU in February 2006 and continued at the field location. The PVC designs were deployed first. The sites were completed in the following order: site 1, site 2, site 4, and site 3. Site 1 received the first structures in early April, 2006 and site 3 received the final PVC structure on May 11, 2006. Bamboo structures were constructed and deployed from May 16 through June 1, 2006 with the same order of sites.

Two methods for plant establishment were used with each structure design:

1. *P. hemitomon* in peat pots
2. *P. hemitomon* stems

The structures were planted with a number of pots that provided an average density of 1 pot per square foot of structure. For the PVC design 30 pots per structure were used, and for the bamboo design 10 pots per structure were used. For the stem-planted structures aerial stems were used from the number of pots that would be used if the structure was planted with pots (approximately 30 stems in the bamboo structures and 90 stems in the PVC structures). *P. hemitomon* was actually planted in peat pots in half of the PVC structures. In the other half it was established from stems. All PVC structures were fenced, except for five replicates of each establishment technique at each site. Nine of the bamboo structures at each site utilized stem establishment and 16 used pot establishment. None of the bamboo structures were left unfenced.

Monitoring

Monitoring parameters were obtained from 5 replicates of each treatment combination at each site. Treatment combinations were:

Structure type	Establishment technique	Grazing treatment	Total No. of Replicates
PVC	Pots	Fenced	15
PVC	Pots	Unfenced	5
PVC	Stems	Fenced	15
PVC	Stems	Unfenced	5
Bamboo	Pots	Fenced	16
Bamboo	Stems	Fenced	9

Vegetation, structural integrity, and buoyancy were monitored quarterly from July 2006 through October 2008. Vegetation cover within each structure was estimated to the nearest 5% by species. Farthest spread of *P. hemitomon* was measured to the nearest cm from each of the four sides of the structure once the plants have grown outside the structure boundary.

Structural integrity was determined by answering the following questions:

- Is the shape maintained?
- Do the fasteners show signs of wear and tear?
- Does the containment fabric show signs of wear and tear?

Where possible the source of wear and tear was identified.

To determine the buoyancy of the structure, the assignment to one of three buoyancy classes were used:

1. floating at or above the water surface
2. submerged floating (0 -15 cm below the water surface)
3. submerged non-floating (>15 cm below the water surface)

If the structure was tilted (i.e. with one side of the structure floating and the other side submerged), the buoyancy class of the majority of the structure's surface was assigned.

Illustration 12. Measurement of root mat depth.

There were 3 replicate surface water samples collected at each site in July, September, and October. Samples were preserved on ice in the field and were frozen at LSU until analysis. Inorganic nutrient concentrations of ammonium, nitrate-nitrite, and phosphate were determined with the standard methods of the LSU Coastal Ecology Institute Analytical Laboratory.

The monitoring plan calls for measurement of root mat depth in October of each year. There was an attempt to measure this parameter on October 24, 2006. However, due to the incredible growth of *P. hemitomon* the structures were extremely heavy and very difficult to lift. Lifting the structures from the water to reveal the root mat causes concern that this procedure could damage the structures. For the five structures that were measured the average mat depth was 40 cm. An attempt was made to core to the root mat at a few structures at site 2 in May 2009. The root mat was found to be highly variable and it was extremely difficult to access structures as a mat formed outside the structures. Reliable estimates would have required complete sacrifice of several structures, and coring was therefore abandoned.

Water Level and Salinity

Soon after deployment of the structures, it became apparent that salinity intrusion might be a problem at some of the sites. To test this, salinity gauges were installed at four locations in August 2006 (Figure 1), although this was not required in the monitoring plan. The first gauge location was installed near the intersection of Hanson Canal and the Gulf Intracoastal Water Way

and is referred to as the Hanson Canal Gauge (HC in Figure 1). The second gauge location was near site 4 and referred to as the South Marsh Gauge (SM). The third gauge location was near site 2, referred to as the North Marsh Gauge (NM). The final gauge was located north of the project site near the boat launch on the Daneco Alligator Farm, referred to as the Turning Basin Gauge (TB).

RESULTS AND DISCUSSION

Artificial Floating Marsh Systems (AFS) Evaluation in Aquaculture Ponds

Performance

Twenty-seven AFS designs were constructed and tested at the LSU AgCenter research ponds between 2004 and 2005 (Table 1). While some of the structures performed well, several structures lost buoyancy and/or suffered from mat disintegration. A description of the structures follows, beginning with those that were failures and ending with those structures that performed well for at least three months of the testing. AFS 4 was the first that failed because its Styrofoam billets became a favorite spot for nutria and muskrat to visit and these animals damaged the burlap mat. These structures were removed from the ponds in October 2004. The second failing design was AFS 2, the second failed design, incorporated a jute mat which disintegrated within a few months after deployment. Also, one of these structures lost buoyancy when the pine frame became water logged. This design was removed from the pond in early March 2005. AFS 8, incorporating burlap but no frame, submerged in November 2004, and then completely disintegrated, with no remains found even after one of the ponds was drained. Four of the five replicates of AFS 10 lost buoyancy when both the coconut mat and the pine frame became waterlogged. These structures were removed from the ponds between November 2004 and March 2005.

All structures were heavily grazed by both nutria and muskrat, and it became apparent that these grazers needed to be excluded from the structures. Exclusion was not possible for AFS designs 1 and 11, built of pine frames and rope mats, and these continued to be heavily grazed. In addition the burlap bags in these designs and some of the ropes had deteriorated. Therefore, AFS 1 and 11 were removed from the ponds in early March 2005. AFS 9 remained buoyant until grazers damaged the fasteners that attached the Styrofoam, so these structures were also removed in early March 2005.

Both the cedar lattice structures (AFS 15, 16, 17, and 18) and the wood gabion structures (AFS 19, 20, and 21) lost buoyancy within several weeks after deployment. Buoyancy was increased by adding bamboo pieces to these structures.

Two of the original pine frames (AFS 6 and 12) were fenced with vinyl coated chicken-wire (crab pot wire) to exclude nutria and muskrats in October 2004, which added a significant amount of weight and required the addition of Styrofoam to increase the buoyancy of these structures when they were fenced. The designs that incorporated either PVC (AFS 3, 5, and 7) or bamboo (AFS 22, 23, and 24) were successful in maintaining buoyancy on their own.

Nutrient levels in the ponds were relatively low, with nitrate-nitrite averaging 0.02 mg/l, ammonium averaging 0.01 mg/l and phosphate averaging 0.04 mg/l. These values are much lower than nutrient concentrations of surface water at Lake Boeuf, which has average concentrations for nitrate-nitrite at 0.07 mg/l, ammonium averaging 4.2 mg/l and phosphate averaging 0.31 mg/l (Sasser 1991). These low nutrient concentrations at the ponds necessitated fertilization of the AFS designs. Structures planted with plugs as well as those structures with coconut or birch mats were fertilized in April 2005. Applying fertilizer to the chicken-wire mat

structures (AFS 19 and 22) required an innovative solution. At the end of June 2005, these chicken-wire mat structures were fertilized with Osmocote® suspended in nylon bags.

Figure 4 shows the analysis of the *P. hemitomon* cover and species diversity as observed in the AFS designs on August 17, 2005 (the last observation before the hurricanes disturbed a few of the structures) using only those structures that were deployed throughout the 2005 growing season (AFS 3, 6, 7, 12, and 15 through 25). When grouped by frame type, the cedar designs tended to have the greatest cover of *P. hemitomon*. However, these structures also had the highest cover immediately after planting (28%). The other structures had an average initial cover of 10%.

By August 2005, a noticeable difference in species diversity was observed among the different frames (Figure 5). Structures that were planted with marsh plugs (intact soil cores) had a significantly higher number of species than those planted with *P. hemitomon* whole plants, belowground, or aboveground material (Figure 5). This is not surprising, since the plugs were obtained from mature natural marshes and contained multiple species at the time they were added to the structure. In contrast, species could only establish on the other AFS designs from local seed sources. Of the structures planted with plugs, the more buoyant frames (PVC and bamboo) had higher species diversity than the less buoyant frames.

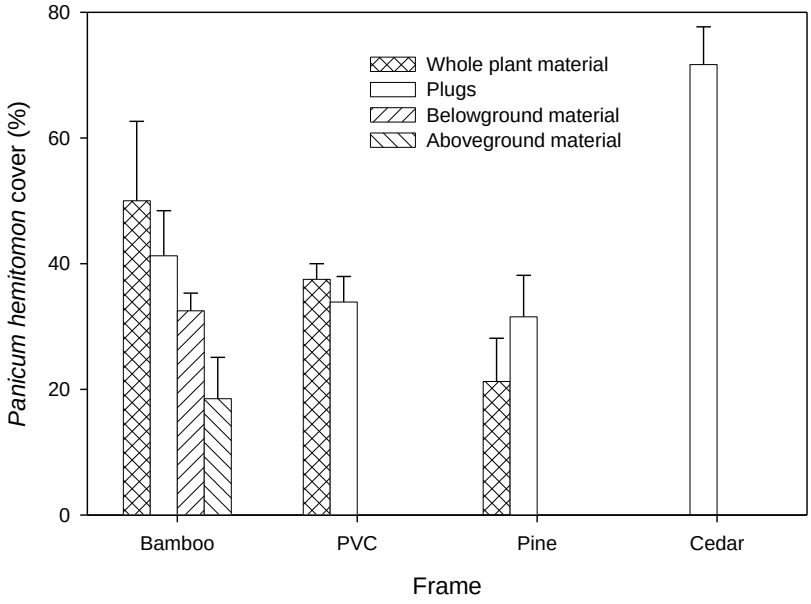

Figure 4. Effect of frame type on *P. hemitomon* cover on August 17, 2005. Only the bamboo frames included treatments that were planted with aboveground material and belowground material.

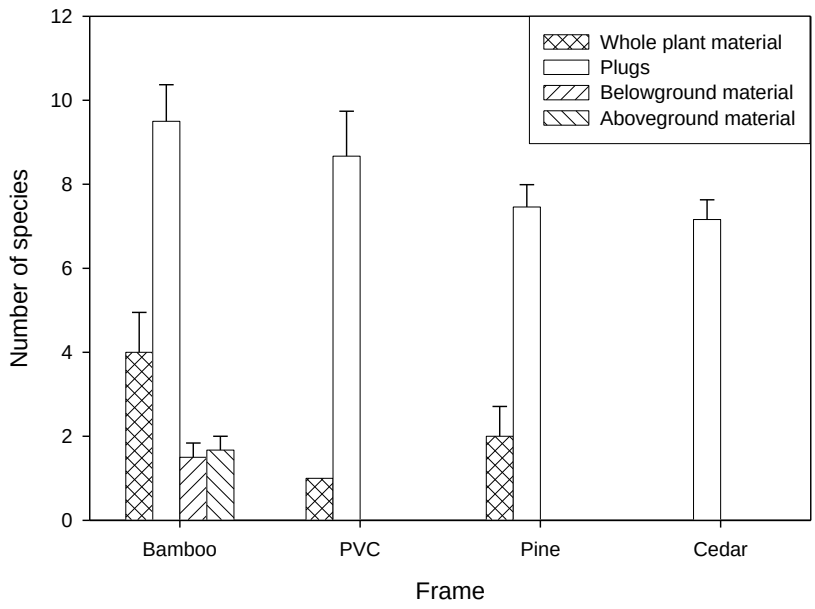

Figure 5. Effect of frame type on the number of species on August 17, 2005. Only the bamboo frames included treatments that were planted with aboveground material and belowground material.

P. hemitomon cover was highest when plant establishment occurred with plugs and the structure contained coconut or chicken-wire or had no mat (Figure 6). The relatively low cover on the straw-coconut mat may be the result of the lower planting density on these mats (initial cover 5%). The lower performance of plugs on birch mats may be due to the establishment of *Ludwigia* sp. which both out-competed *P. hemitomon* late in the growing season, and reduced the buoyancy of these structures. When established from whole plant materials, the highest *P. hemitomon* cover occurred on structures with birch mats, followed by coconut mats, and chicken wire mats (Figure 6). Establishment from belowground material resulted in similar cover to that established from whole plant material irrespective of mat type. On the coconut mat, establishment from aboveground material resulted in the same *P. hemitomon* cover reached by whole plant or belowground material. In contrast, establishment from aboveground material failed while grown under hydroponic conditions on chicken-wire mats.

The poor performance of *P. hemitomon* on chicken-wire mats when established from sources other than plugs may have resulted from our inability to fertilize these structures in April. Plugs provide their own substrate and were fertilized early in the season. The chicken-wire mat structures were fertilized (AFS 19 and 22) at the end of June 2005 when a method was devised for applying fertilizer to these structures. However, this fertilizer application was too late to have the aboveground material catch up to the whole plants and belowground material planted structures.

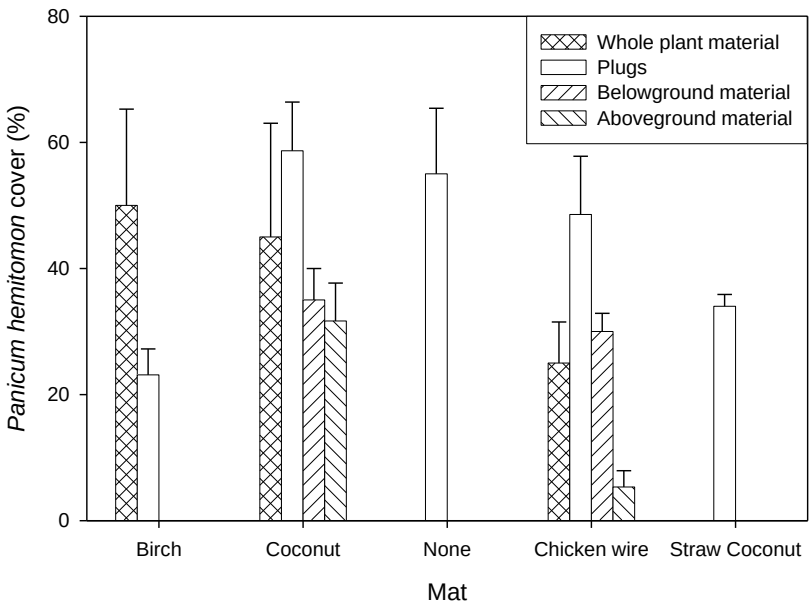

Figure 6. Effect of mat type on *P. hemitomon* cover on August 17, 2005. Only the coconut and chicken wire mats included treatments that were planted with aboveground material and belowground material.

Substrate had some effects on *P. hemitomon* performance (Figure 7). Plugs performed best without any substrate, but this may be driven by the more densely planted lattice designs (AFS 15, 16, 17, and 18), which make up the majority of the structures without substrate. The other structures without substrate are AFS 12, 19, and 22. The performance of plugs was similar for hardwood mulch and peat-bagasse substrates. When established from whole plant, belowground, and aboveground material, cover was greater on the peat-bagasse substrate than when grown under hydroponic conditions. This is probably related to our inability to properly fertilize the hydroponic structures early in the growing season.

The substrate also affected species diversity (Figure 8). When established from plugs, highest species diversity occurred on the hardwood mulch, followed by hydroponic and the lowest diversity on peat-bagasse. In contrast, when established from whole plant, aboveground, or belowground material, no other species besides *P. hemitomon* established under hydroponic conditions, with a few more species establishing from seed when a substrate was available.

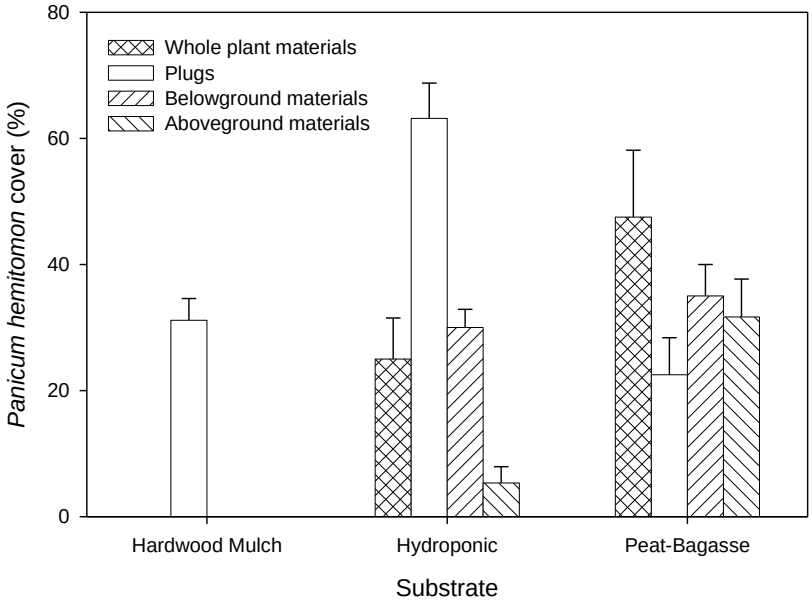

Figure 7. Effect of substrate type on *P. hemitomon* cover on August 17, 2005. Only the peat-bagasse and the hydroponic treatmentswere planted with aboveground material or belowground material.

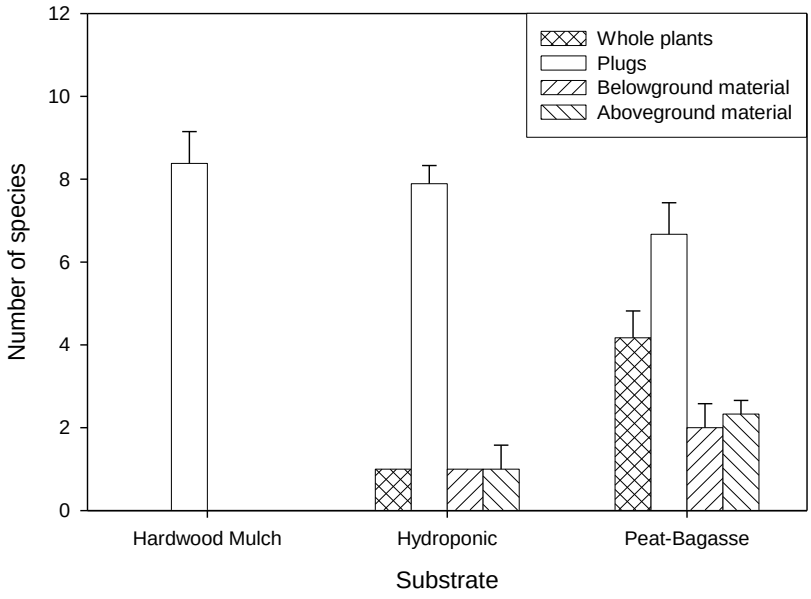

Figure 8. Effect of substrate type on the number of species on August 17, 2005. Only the peat-bagasse and the hydroponic treatments were planted with aboveground material or belowground material.

Plant Establishment

The highest shoot production in the greenhouse resulted when using whole plants (aerial stems and rhizomes) compared to rhizome and aerial stem material. By 28 days almost all whole plants produced shoots, while nearly 75% of belowground material with either 1 or 2 nodes yielded shoots (Figure 9). Shoot production from stem pieces was lowest, with 50% of stems producing shoots by 28 days.

Evaluations were also conducted on the effect of fertilization on shoot production of *P. hemitomon* stem and rhizome material (Figure 10). In this trial, randomly chopped stem or rhizome material was used, with variable number of nodes per piece. Those pieces were spread evenly across six 2-inch thick coconut fiber squares that were saturated with water. Half of the coconut fiber squares were fertilized and the other half were left unfertilized. In both treatments, rhizome pieces outperformed stem pieces throughout the experiment (Figure 10). It was also found that the addition of fertilizer greatly improved shoot production in both stem pieces and belowground material. Thus, using randomly chopped stem or rhizome material could be a viable way to propagate *P. hemitomon*, and nutrient availability in the water will improve shoot production.

Illustration 13. Root mat formation from discarded stems

Plants were regularly cut to promote root development in the process of growing plants for the field deployment stage of the project. Some of the cut stems were left in a tray with water and developed a vigorous root mat. This contributed to our conclusion that plant establishment from aerial stems is an option that should be tested under field conditions.

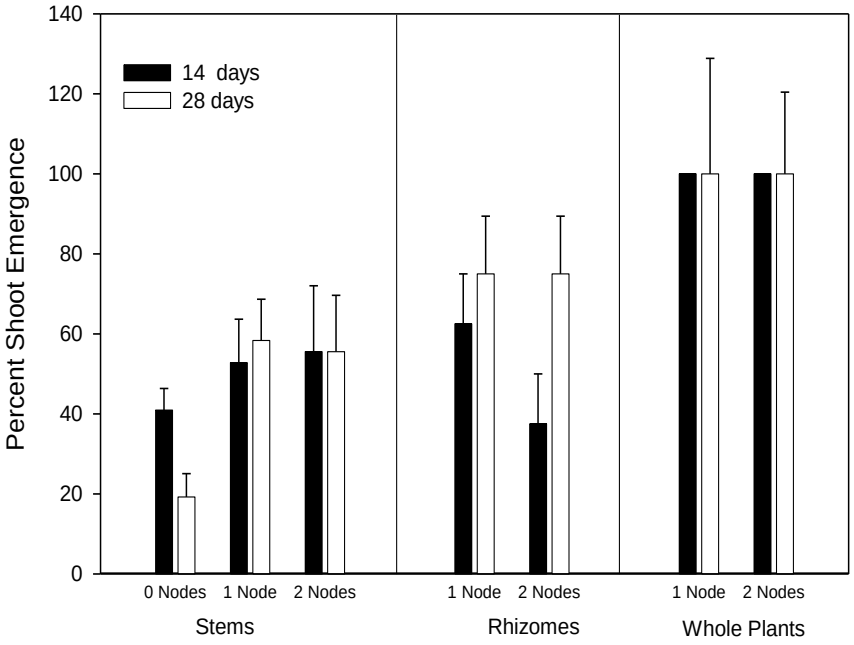

Figure 9. Effect of plant material on shoot development.

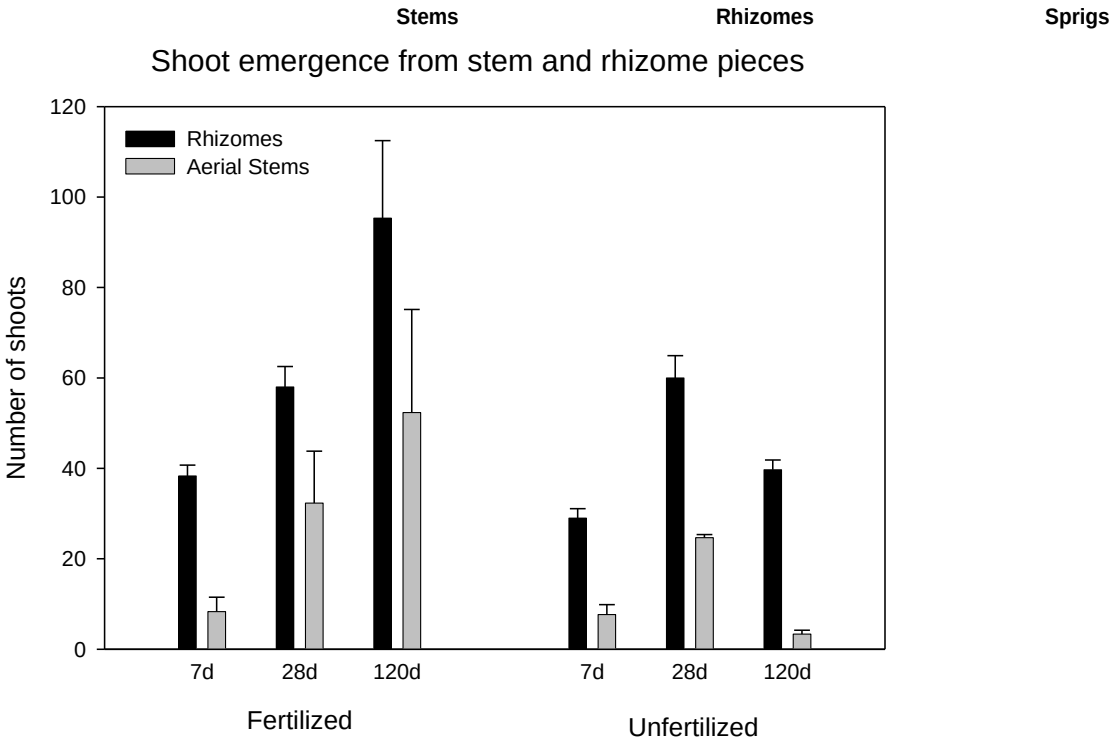

Figure 10. Effect of plant material and fertilization on shoot development.

Optimization of Plant Response

Experiment-1: Evaluating the effects of nutrient loading rate and flooding depth

P. hemitomon cumulative stem height associated with Experiment-1.v1 (Figure 11) exhibited a highly significant main effect of time (Wilk's lambda: $F_{3,30} = 73.62$; $p < 0.0001$) as well as a significant time by nutrient interactive effect (Pillai's trace: $F_{9,96} = 4.78$; $p = 0.0052$). However, the time by hydrology (Wilk's lambda: $F_{3,30} = 1.45$; $p = 0.2483$) and time by nutrient by hydrology interactive effects (Pillai's trace: $F_{9,96} = 1.01$; $p = 0.4413$) were not significant.

Similar but slightly different results were associated with Experiment-1.v2 (Figure 12). A highly significant main effect of time was observed (Wilk's lambda: $F_{2,31} = 77.05$; $p < 0.0001$) as were significant time by nutrient (Pillai's trace: $F_{6,64} = 3.45$; $p = 0.0052$) and time by hydrology interactive effects (Wilk's lambda: $F_{2,31} = 9.53$; $p = 0.0006$). The time by nutrient by hydrology interactive effect was marginally significant (Pillai's trace: $F_{2,24} = 2.24$; $p = 0.0504$). As expected, cumulative stem height increased over time, and greater cumulative stem height was attained by plants exposed to elevated nitrogen availability. Greater cumulative stem height was associated with saturated, but not inundated conditions in Experiment-1.v2.

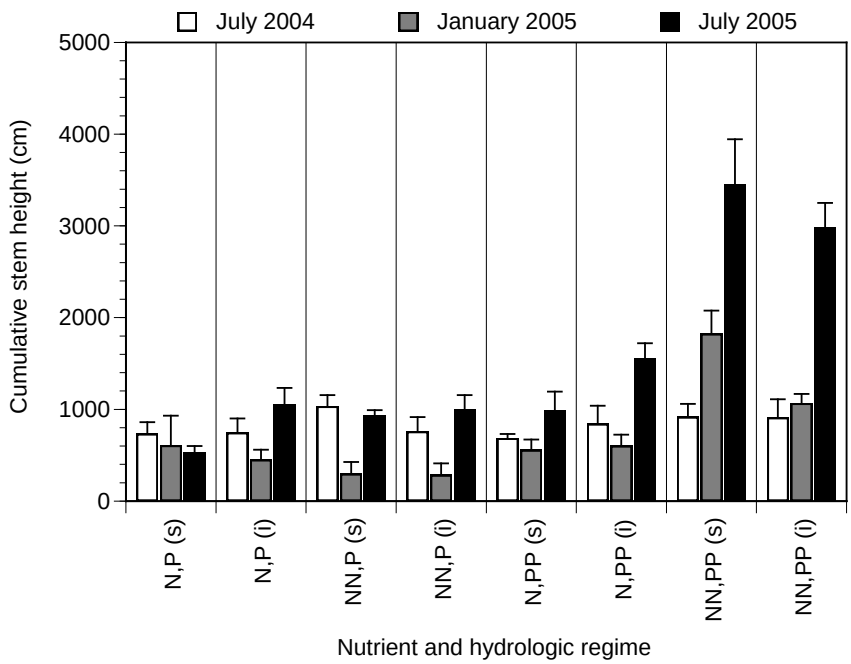

Figure 11. The effect of manipulated nutrient availability and hydrology on P. hemitomon cumulative stem height (cm) measured monthly over a 12-month period from July 2004 to July 2005 (Experiment-1.v1). Treatment codes are as follows: N,P = low nitrogen and low phosphorous; NN,P = high nitrogen and low phosphorous; N,PP = low nitrogen and high phosphorous; NN,PP = high nitrogen and high phosphorous; s = saturated; i = inundated. Value are means ± SE (n = 5).

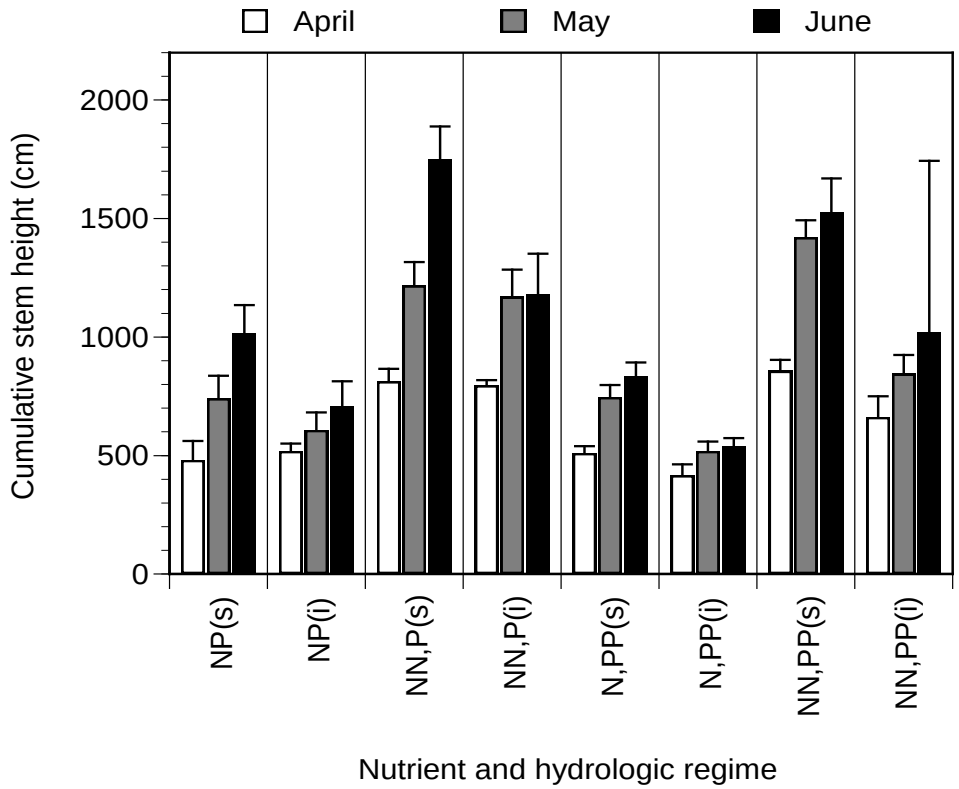

Figure 12. The effect of manipulated nutrient availability and hydrology on *P. hemitomon* cumulative stem height (cm), measured monthly over a 3-month period from April 2006 to June 2006 (Experiment-1.v2). Treatment codes are as follows: N,P = low nitrogen and low phosphorous; NN,P = high nitrogen and low phosphorous; N,PP = low nitrogen and high phosphorous; NN,PP = high nitrogen and high phosphorous; s = saturated; i = inundated. Values are means ± SE (n = 5).

Total stem number associated with Experiment-1.v1 (Figure 13, left panel) exhibited a highly significant main effect of nutrient regime ($F_{7,32}$ = 39.92; p < 0.0001) but not a significant main effect of hydrologic regime ($F_{1,32}$ = 0.31; p = 0.5788). The nutrient by hydrology interactive effect was significant ($F_{3,32}$ = 4.13; p = 0.0140). A highly significant difference was also observed for mean stem height (Figure 14, left panel) according to the main effects of both nutrient ($F_{3,32}$ = 9.52; p = 0.0001) and hydrologic regime ($F_{1,32}$ = 18.53; p < 0.0001). The nutrient by hydrology interactive effect was not significant ($F_{3,32}$ = 1.56; p = 0.2194). As observed in experiment 1.v1, total stem number associated with Experiment-1.v2 (Figure 13, right panel) exhibited highly significant main effects of both nutrient ($F_{3,32}$ = 13.07; p < 0.0001) and hydrologic regime ($F_{1,32}$ = 29.64; p < 0.0001), although the nutrient by hydrology interactive effect was not significant ($F_{3,32}$ = 1.33; p = 0.2829).

Mean stem height associated with Experiment-1.v2 (Figure 14, right panel) did not differ significantly according to the main effect of nutrient regime ($F_{3,32}$ = 2.16; p = 0.1115), but the main effect of hydrologic regime was significant ($F_{1,32}$ = 5.07; p = 0.0314). The nutrient by hydrology interactive effect was not significant ($F_{3,32}$ = 1.51; p = 0.2301).

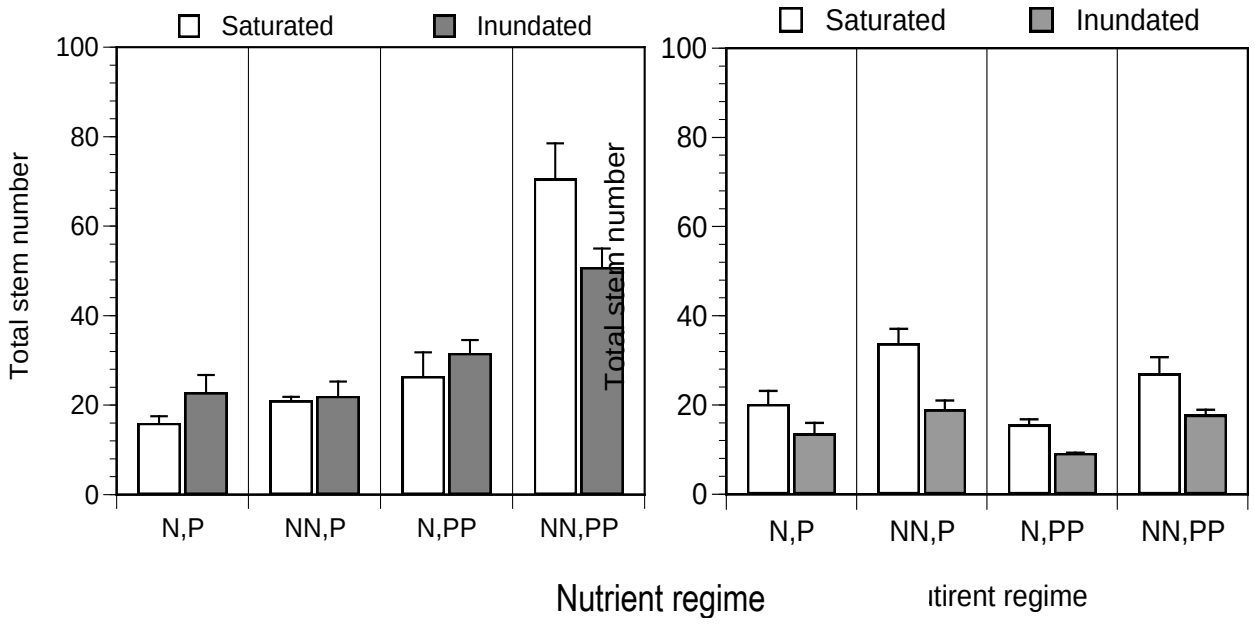

Figure 13. The effect of manipulated nutrient availability and hydrology on *P. hemitomon* total stem number measured after 12 months of growth for Experiment-1.v1 (left panel) and after 4 months of growth for Experiment-1.v2 (right panel). Treatment codes are as follows: N,P = low nitrogen and low phosphorous; NN,P = high nitrogen and low phosphorous; N,PP = low nitrogen and high phosphorous; NN,PP = high nitrogen and high phosphorous. Values are means ± SE (n = 5).

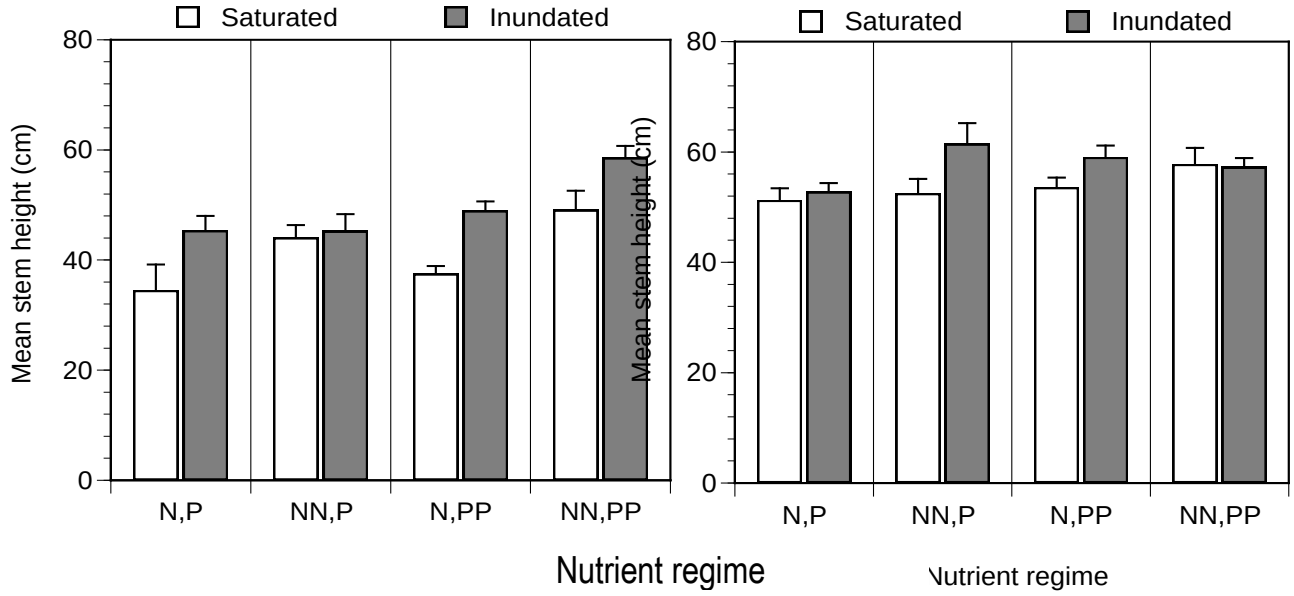

Figure 14. The effect of manipulated nutrient availability and hydrology on *P. hemitomon* mean stem height (cm) measured after 12 months of growth for Experiment-1.v1 (left panel) and after 4 months of growth for Experiment-1.v2 (right panel). Treatment codes are as follows: N,P = low nitrogen and low phosphorous; NN,P = high nitrogen and low phosphorous; N,PP = low nitrogen and high phosphorous; NN,PP = high nitrogen and high phosphorous. Values are means ± SE (n = 5).

P. hemitomon net CO_2 assimilation was measured for both versions of Experiment-1, with different results obtained for the two versions. No significant differences were observed in Experiment-1.v1 (Figure 15, left panel) in relation to main effect of nutrient ($F_{3,72}$ = 0.62; p = 0.6066) or hydrologic regime ($F_{1,72}$ = 2.69; p = 0.1054), nor was the nutrient by hydrology interactive effect significant ($F_{3,72}$ = 0.83; p = 0.4836). For Experiment-1.v2 (Figure 15, right panel) the main effects of both nutrient ($F_{3,72}$ = 3.69; p = 0.0156) and hydrologic regime ($F_{1,72}$ = 20.28; p < 0.0001) were significant, although the nutrient by hydrology interactive effect was not ($F_{3,72}$ = 0.60; p = 0.6140). Such differences could be attributed to factors including different *P. hemitomon* ecotypes, variation in tissue age, or concordant differences in tissue nutrient levels and variation in greenhouse conditions.

P. hemitomon tissue nitrogen content for Experiment-1.v1 (Figure 16, left panel) was relatively uniform with respect to all factors and levels. No significant differences were observed for either the main effect of nutrient ($F_{3,32}$ = 1.30; p = 0.2913) or hydrologic regime ($F_{1,32}$ = 2.31; p = 0.1387). Likewise, no significant differences were associated with the nutrient by hydrology interactive effect ($F_{3,32}$ = 0.43; p = 0.7325). *P. hemitomon* tissue nitrogen content associated with Experiment-1.v2 (Figure 16, right panel) did not vary significantly with respect to the main effect of nutrient regime ($F_{3,32}$ = 1.96; p = 0.1394) but did when the main effect of hydrologic

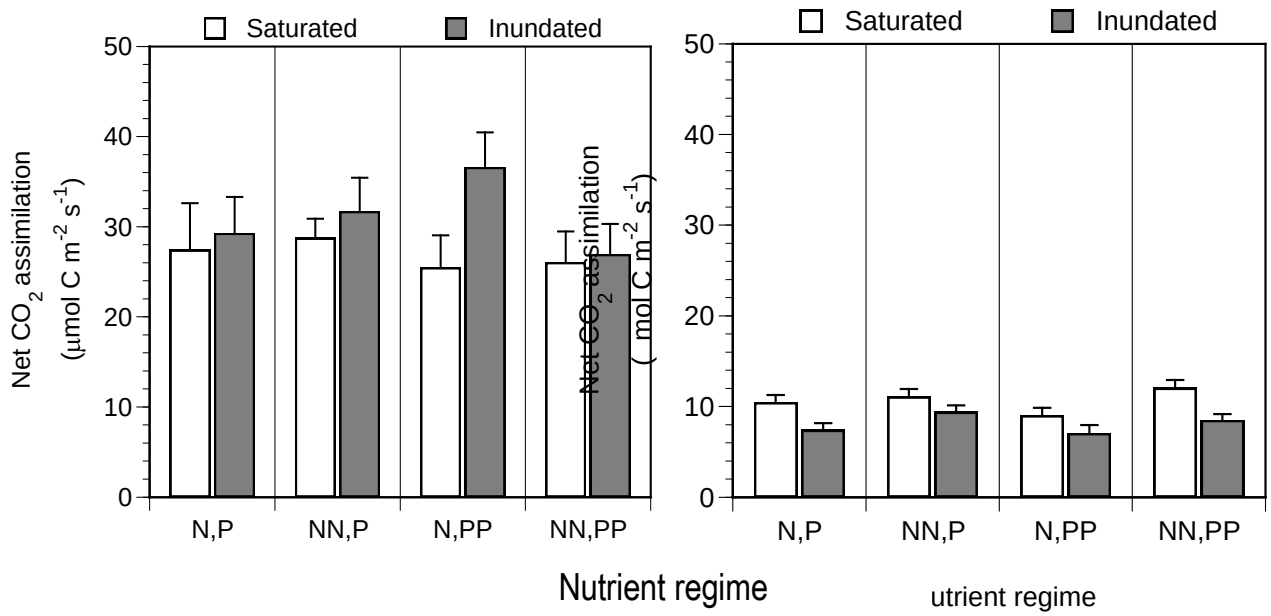

Figure 15. The effect of manipulated nutrient availability and hydrology on *P. hemitomon* net CO2 assimilation (µmol C m-2 s-1) associated with Experiment-1.v1 (left panel) and Experiment-1.v2 (right panel). Treatment codes are as follows: N,P = low nitrogen and low phosphorous; NN,P = high nitrogen and low phosphorous; N,PP = low nitrogen and high phosphorous; NN,PP = high nitrogen and high phosphorous. Values are means ± SE (n = 5).

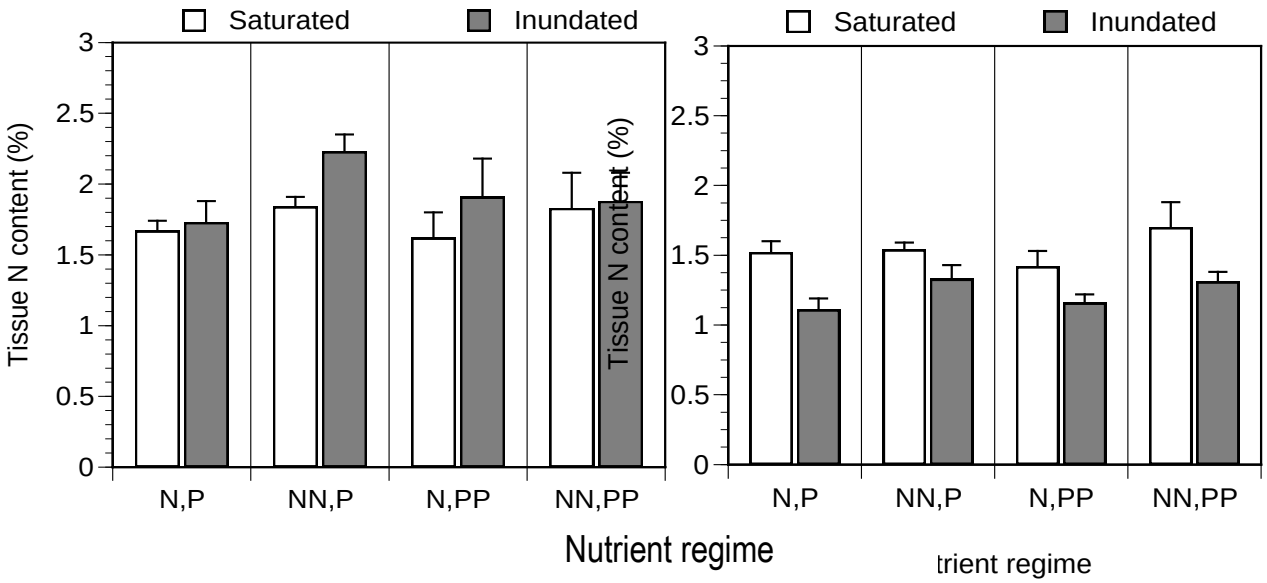

Figure 16. The effect of manipulated nutrient availability and hydrology on *P. hemitomon* leaf tissue N content (%) associated with Experiment-1.v1 (left panel) and Experiment-1.v2 (right panel). Treatment codes are as follows: N,P = low nitrogen and low phosphorous; NN,P = high nitrogen and low phosphorous; N,PP = low nitrogen and high phosphorous; NN,PP = high nitrogen and high phosphorous. Values are means ± SE (n = 5).

regime was considered ($F_{1,32}$ = 19.34; p < 0.0001). The nutrient by hydrology interactive effect was not significant ($F_{3,32}$ = 0.44; p = 0.7237). The greater percentage of tissue nitrogen associated with Experiment-1.v1 could be an age effect, whereas the greater percentage of tissue nitrogen exhibited by plants grown in the presence of saturated conditions in Experiment-1.v2 could be a result of greater nutrient absorbance resulting from more robust root biomass.

P. hemitomon photosynthetic nitrogen use-efficiency (PNUE) was measured in both Experiment-1 versions. Interestingly, photosynthetic nitrogen use-efficiencies were relatively uniform across all factors and levels for both phases. PNUE associated with Experiment-1.v1 (Figure 17, left panel) did not exhibit a significant difference with respect to either nutrient regime ($F_{3,32}$ = 1.07; p = 0.3760) or hydrologic regime ($F_{1,32}$ = 0.08; p = 0.7851). The nutrient by hydrologic interactive effect was also not significant ($F_{3,32}$ = 0.53; p = 0.6646). For Experiment-1.v2 (Figure 17, right panel) a significant difference was not observed with respect to either nutrient regime ($F_{3,32}$ = 0.87; p = 0.4654) or hydrologic regime ($F_{1,32}$ = 0.46, p = 0.5045). The nutrient by hydrology interactive effect similarly was not significant ($F_{3,32}$ = 0.12; p = 0.9491).

Linear regression analyses of *P. hemitomon* PNUE as a factor of leaf tissue nitrogen content were performed on each nutrient by hydrology treatment combination for both phases of the experiment (Table 2). Relationships for the low nitrogen and low phosphorous treatments regardless of hydrologic regime were strongest in Experiment-1.v1 (R^2 = 0.59 and 0.73 respectfully), whereas in Experiment-1.v2 the high nitrogen and high phosphorous treatments

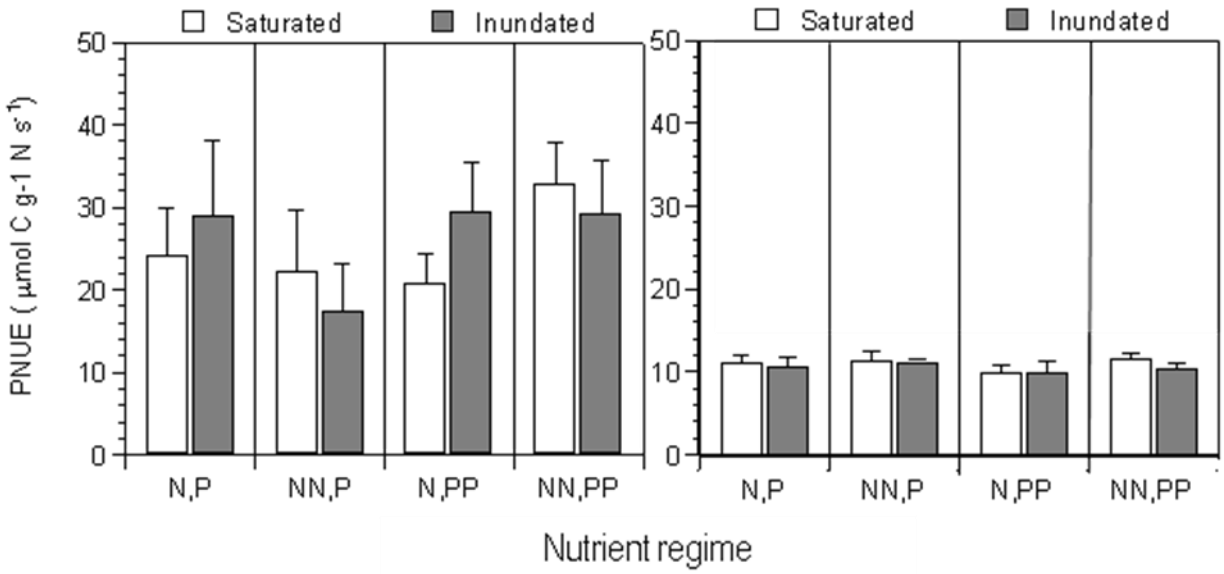

Figure 17. The effect of manipulated nutrient availability and hydrology on *P. hemitomon* PNUE (µmol C g-1 N s-1) associated with Experiment-1.v1 (left panel) and Experiment-1.v2 (right panel), measured at peak standing crop as a factor of leaf tissue N content (g N cm-2) in both phases. Treatment codes are as follows: N,P = low nitrogen and low phosphorous; NN,P = high nitrogen and low phosphorous; N,PP = low nitrogen and high phosphorous; NN,PP = high nitrogen and high phosphorous. Values are means ± SE (n = 5).

regardless of hydrologic regime exhibited the strongest relationships (R^2 = 0.82 and 0.59 respectfully). In both cases decreasing PNUE was associated with increases in leaf nitrogen content. The relationships of all other treatment combinations for either phase exhibited very weak non-significant trends.

P. hemitomon aboveground biomass associated with Experiment-1. v2 (Figure 18) exhibited a significant difference with respect to the main effects of both nutrient ($F_{3,32}$ = 31.13; p = 0.0001) and hydrologic regime ($F_{1,32}$ = 16.35; p = 0.0003). However, the nutrient by hydrology interactive effect was not significant ($F_{3,32}$ = 1.34; p = 0.2788). Greater aboveground biomass was associated with elevated nitrogen availability. Aboveground biomass was also greater overall under saturated conditions. The same hydrologic effect was also observed under low nitrogen availability.

P. hemitomon total belowground root and rhizome biomass associated with Experiment-1.v2 (Figure 19) was similar to aboveground biomass in that significant differences were observed with respect to the main effects of both the nutrient ($F_{3,32}$ = 8.64; p = 0.0002) and hydrologic regimes ($F_{1,32}$ = 119.88; p < 0.0001). The nutrient by hydrology interactive effect was not significant ($F_{3,32}$ = 1.65; p = 0.1964). Elevated nitrogen availability and saturated conditions resulted in the greatest belowground production.

Table 2. Line equations and associated levels of significance (R^2 and p-values) from linear regression analyses of *P. hemitomon* PNUE (μmol C g^{-1} N s^{-1}) associated with both versions of Experiment 1 measured at peak standing crop as a factor of leaf tissue nutrient content (g N cm^{-2}).

Experiment-1.v1

Treatment	Line equation	R^2 (p-value)
N,P (saturated)	y = 100.7x + -78.94	0.59 (0.1274)
N,P (inundated)	y = -81.6x + 115.55	0.73 (0.0650)
NN,P (saturated)	y = -77.3x + 109.89	0.20 (0.4490)
NN,P (inundated)	y = -31.3x + 60.28	0.16 (0.4922)
N,PP (saturated)	y = 4.1x + 16.71	0.01 (0.8266)
N,PP (inundated)	y = -0.2x + 29.80	0.00 (0.9902)
NN,PP (saturated)	y = -6.0x + 39.68	0.03 (0.7587)
NN,PP (inundated)	y = -5.1.x + 35.26	0.01 (0.8692)

Experiment-1.v2

Treatment	Line equation	R^2 (p-value)
N,P (saturated)	y = -10.6x + 2.12	0.39 (0.2534)
N,P (inundated)	y = -8.1x + 1.65	0.17 (0.4796)
NN,P (saturated)	y = 3.3x + 8.55	0.01 (0.8652)
NN,P (inundated)	y = 1.5x + 1.01	0.08 (0.6285)
N,PP (saturated)	y = 5.4x + 5.46	0.19 (0.4625)
N,PP (inundated)	y = -15.2x + 2.09	0.14 (0.5285)
NN,PP (saturated)	y = -6.2x + 18.38	0.82 (0.0322)*
NN,PP (inundated)	y = -11.3x + 19.83	0.59 (0.1274)

* Significant difference ($p < 0.05$).

Illustration 14. Experiment-1.v2. Left plant represents low N and P x inundated. Right plant represents low N and P x saturated.

Illustration 15. Experiment-1v2. Left plant represents high N and P x saturated. Right plant represents high N and P x inundated.

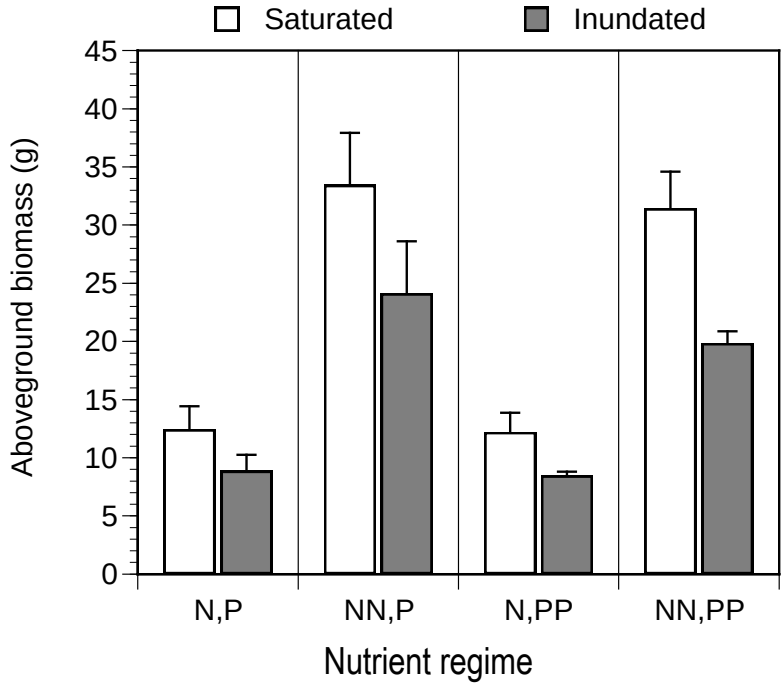

Figure 18. The effect of nutrient loading rate and flooding stress on *P. hemitomon* aboveground biomass. N,P = low N and low P; NN,P = high N and low P; N,PP = low N and high P; NN,PP = high N and high P. Values are means ± SE (n = 5).

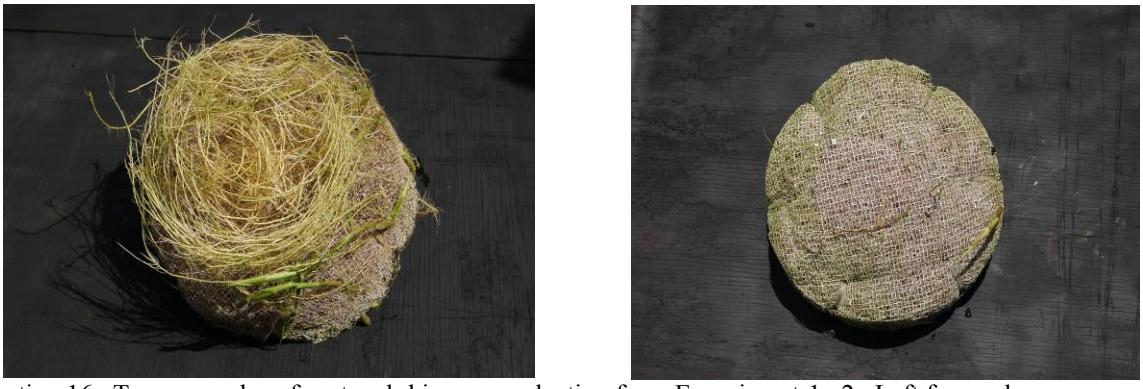

Illustration 16. Two examples of root and rhizome production from Experiment-1.v2. Left frame shows belowground production under high N and P x saturated, right frame shows belowground under low N and P x inundated.

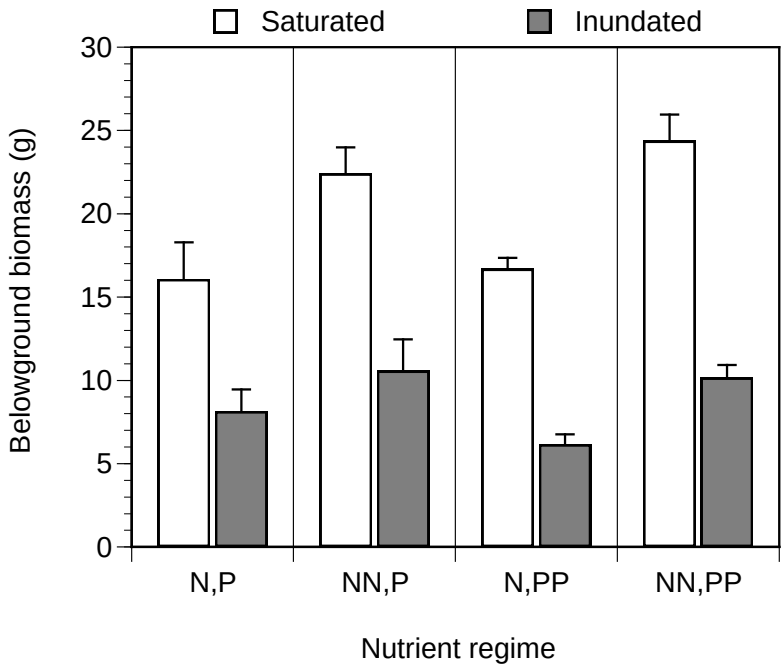

Figure 19. The effect of nutrient loading rate and flooding stress on *P. hemitomon* belowground biomass. N,P = low N and low P; NN,P = high N and low P; N,PP = low N and high P; NN,PP = high N and high P. Values are means ± SE (n = 5).

Total rhizome length associated with Experiment-1.v2 (Figure 20, left panel) followed suite with most other metrics of biomass in that it varied significantly with respect to the main effect of fertilization and that nitrogen was more influential. The main effect of hydrologic regime was also significant ($F_{1,32} = 78.72$; $p < 0.0001$). Not surprising, the nutrient by hydrology interactive effect was not significant ($F_{3,32} = 1.21$; $p = 0.3229$). As was observed with total belowground biomass, saturated conditions were more favorable for rhizome growth, as was elevated nitrogen availability.

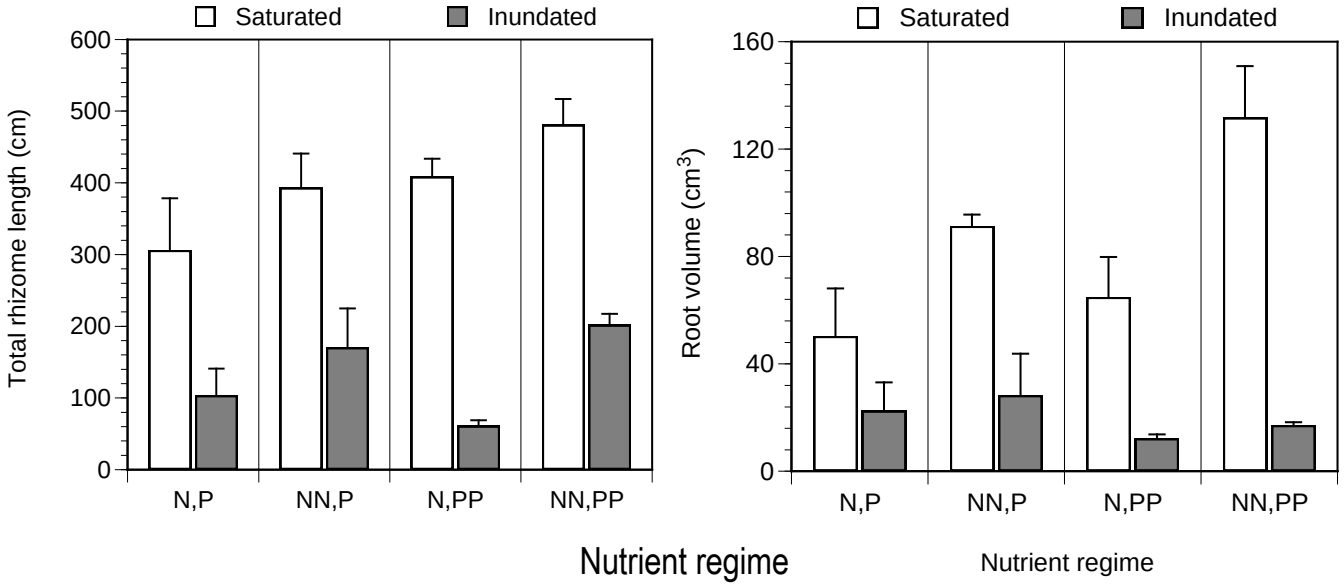

Figure 20. The effect of manipulated nutrient availability and hydrology on P. hemitomon total rhizome length (cm) (left panel) and root volume (cm3) (right panel) associated with Experiment-1.v2, measured at harvest after 4 months of growth. Treatment codes are as follows: N,P = low nitrogen and low phosphorous; NN,P = high nitrogen and low phosphorous; N,PP = low nitrogen and high phosphorous; NN,PP = high nitrogen and high phosphorous. Values are means ± SE (n = 5).

Root volume associated with Experiment-1.v2 (Figure 20, right panel) was strongly influenced by the main effects of nutrient ($F_{3,32} = 4.09$; $p = 0.0145$) and hydrologic regime ($F_{1,32} = 51.71$; $p < 0.0001$). Interestingly, the nutrient by hydrology interactive effect was also significant ($F_{3,32} = 4.14$; $p = 0.0138$). The greatest root volume, much like that of total belowground biomass, was associated with elevated nitrogen availability and saturated conditions. It is also worth noting that root volume was less when inundated conditions prevailed, regardless of nutrient regime.

As anticipated based on results associated with individual measures of above- and belowground biomass, total biomass associated with Experiment-1.v2 (Figure 21) varied significantly with respect to the main effects of both nutrient ($F_{3,32} = 29.09$; $p < 0.0001$) and hydrologic regime ($F_{1,32} = 60.19$; $p < 0.0001$). The nutrient by hydrology interactive effect was not significant ($F_{3,32} = 1.92$; $p = 0.1456$).

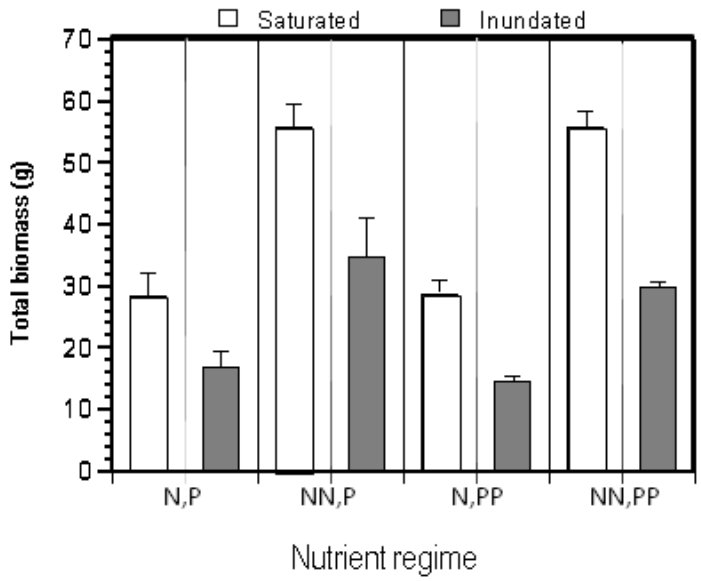

Figure 21. The effect of nutrient loading rate and flooding stress on P. hemitomon total biomass for Experiment-1.v2. (s) = saturated and (i) = inundated: N,P = low N and low P; NN,P = high N and low P; N,PP = low N and high P; NN,PP = high N and high P. Values are means ± SE (n = 5).

P. hemitomon root specific gravity was measured in both Experiment-1.v1 and Experiment-1.v2. For Experiment-1.v1 (Figure 22, left panel) neither the main effect of nutrient regime ($F_{3,32}$ = 1.62; p = 0.2052) nor hydrologic regime ($F_{1,32}$ = 0.05; p = 0.8303) were significant. The nutrient by hydrology interactive effect was not significant either ($F_{3,32}$ = 1.00; p = 0.4066). With respect to Experiment-1.v2 (Figure 22; right panel), a significant nutrient regime main effect was not observed ($F_{3,32}$ = 1.41; p = 0.2576), although the main effect of hydrologic regime was significant ($F_{1,32}$ = 4.67; p = 0.0382). The nutrient by hydrology interactive effect was not significant ($F_{3,32}$ = 0.11; p = 0.9521). The trend for greater root specific gravity (larger values) under inundated conditions was not expected in Experiment -1.v2. Lower specific gravity values are typically associated with hydrologic inundation because of soil hypoxia and its influence on aerenchyma development.

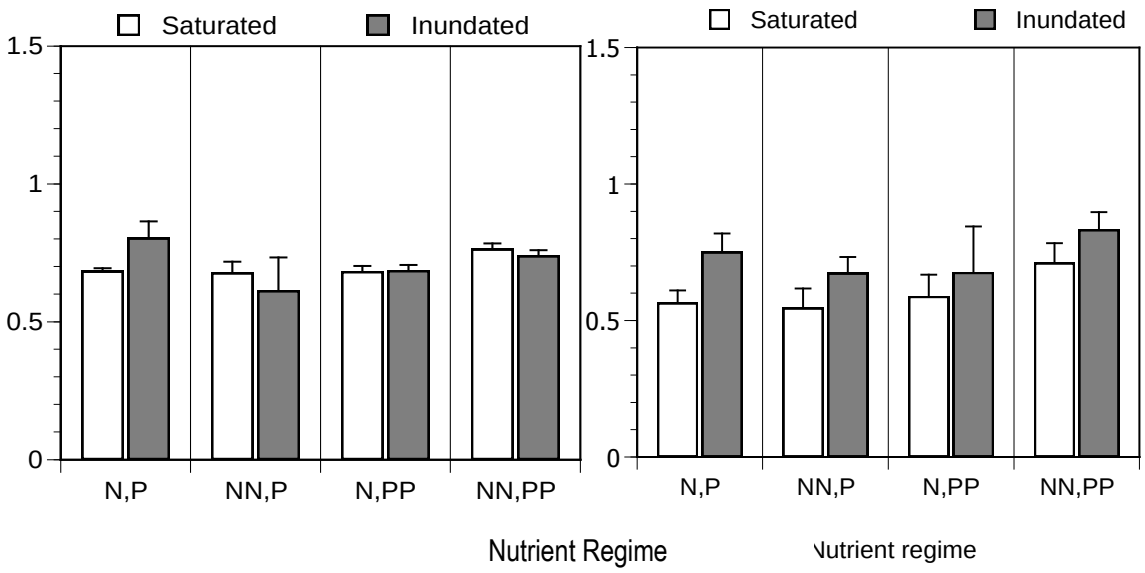

Figure 22. The effect of manipulated nutrient availability and hydrology on *P. hemitomon* root specific gravity associated with Experiment-1.v1 (left panel) and Experiment-1.v2 (right panel), measured on live root tissue immediately prior to experimental harvest in both phases. Treatment codes are as follows: N = low nitrogen; NN = high nitrogen; P = low phosphorous; PP = high phosphorous. Values are means ± SE (n = 5).

P. hemitomon root:shoot ratios associated with Experiment-1.v2 (Figure 23) were calculated to elucidate the relative contribution of above- and belowground biomass to total biomass. Root:shoot ratio exhibited a significant main effect of nutrient regime ($F_{3,32} = 12.31$; $p < 0.0001$) as well as a significant main effect of hydrologic regime ($F_{1,32} = 13.41$; $p = 0.0009$). The nutrient by hydrology interactive effect was not significant ($F_{3,32} = 0.24$; $p = 0.8650$). Root:shoot ratios associated with low nitrogen availability were clearly greater than those associated with high nitrogen availability. For each individual treatment, ratios associated with saturated conditions were greater than those associated with inundated conditions.

P. hemitomon individual root diameter associated with Experiment-1.v2 (Table 3) did not vary significantly according to the main effect of nutrient regime ($F_{3,152} = 0.56$; $p = 0.6145$). On the other hand, the main effect of hydrologic regime was significant ($F_{1,152} = 6.82$; $p = 0.0099$), but the nutrient by hydrology interactive effect was not significant ($F_{3,152} = 1.84$; $p = 0.1421$). As would be expected, mean root diameter was slightly greater when inundated conditions prevailed.

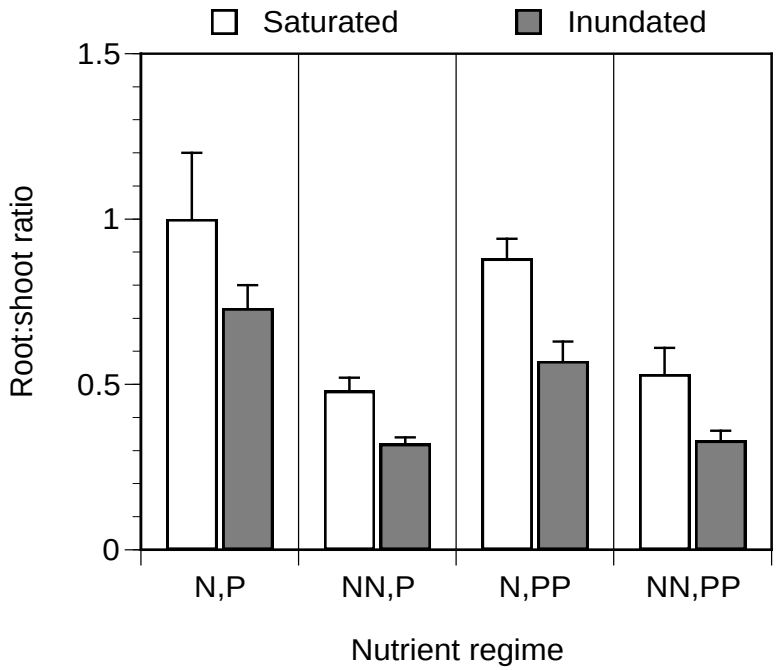

Figure 23. The effect of manipulated nutrient availability and hydrology on *P. hemitomon* root:shoot ratios associated with Experiment-1.v2, derived from dry above- and belowground biomass harvested after 4 months of growth. Treatment codes are as follows: N = low nitrogen; NN = high nitrogen; P = low phosphorous; PP = high phosphorous. Values are means ± SE (n = 5).

P. hemitomon individual root length associated with Experiment-1.v2 (Table 3) did not exhibit a significant main effect of nutrient regime ($F_{3,152}$ = 1.99; p = 0.1185), although a significant hydrologic effect was observed ($F_{1,152}$ = 115.81; p < 0.0001). The nutrient by hydrology interactive effect was not significant ($F_{3,152}$ = 1.88; p = 0.1351). Although not significant, there was trend for greater root length under low nitrogen availability and saturated conditions. Whereas the effect of hydrologic regime was similar at both the individual root and complete root system levels, it is interesting that greater individual root length and tip numbers were associated with low nitrogen availability, whereas greater total root biomass and root volume were associated with elevated nitrogen availability.

P. hemitomon individual root volume associated with Experiment-1.v2 (Table 3) did not exhibit a significant response to the main effect of nutrient regime ($F_{3,152}$ = 0.15; p = 0.9296), although the main effect of hydrologic regime was significant ($F_{1,152}$ = 155.38; p < 0.0001). The nutrient by hydrologic interactive effect was not significant ($F_{3,152}$ = 2.29; p = 0.0808). Individual root volume responded like whole-plant root volume in that greater volume was observed under saturated, not inundated conditions.

Table 3. The effect of manipulated nutrient availability and hydrology on P. hemitomon individual root diameter (mm), root length (cm), root volume (cm3), and number of root tips associated with Experiment-1.v2. All measurements were performed on live root tissue sampled immediately prior to experimental harvest. Values are means ± SE (n = 5).

Treatment	Diameter (mm)	Length (cm)
N,P (saturated)	0.43±0.024[a]	303.25±47.23[a]
N,P (inundated)	0.50±0.044[a]	119.45±37.96[b]
NN,P (saturated)	0.46±0.014[a]	240.99±21.14[a]
NN,P (inundated)	0.45±0.019[a]	71.22±12.88[b]
N,PP (saturated)	0.44±0.019[a]	329.75±31.89[a]
N,PP (inundated)	0.53±0.022[a]	43.62±6.17[b]
NN,PP (saturated)	0.46±0.008[a]	250.20±24.47[b]
NN,PP (inundated)	0.49±0.020[a]	58.57±8.26[b]
F – value $_{(df\ 7,32)}$	2.00[NS]	18.20[**]

Treatment	Volume (cm^3)	Tips (#)
N,P (saturated)	0.37±0.060[a]	1169.70±182.34[a]
N,P (inundated)	0.17±0.044[b]	352.05±87.82[b]
NN,P (saturated)	0.43±0.038[a]	872.60±70.05[a]
NN,P (inundated)	0.09±0.013[b]	290.25±61.48[b]
N,PP (saturated)	0.46±0.032[a]	1250.45±138.76[a]
N,PP (inundated)	0.08±0.005[b]	197.15±23.49[b]
NN,PP (saturated)	0.42±0.037[a]	950.70±96.60[a]
NN,PP (inundated)	0.09±0.010[b]	201.55±23.41[b]
F – value $_{(df\ 7,32)}$	23.24[**]	20.08[**]

[a] Means with the same letter in the same column are not statistically different ($p < 0.05$) based on Tukey's multiple comparison procedure for all possible pairwise comparisons.
[**] Highly significant difference ($p < 0.01$); [NS] non-significant difference ($p > 0.05$).

The number of root tips per individual root did not vary significantly with respect to the main effect of nutrient regime ($F_{3,152} = 1.85$; $p = 0.1413$), although it did when hydrologic regime was considered ($F_{1,152} = 129.26$; $p < 0.0001$). The nutrient by hydrology interactive effect was not significant ($F_{3,152} = 1.92$; $p = 0.1282$). There was a weak trend for a greater number of root tips associated with low nitrogen availability, and it was obvious that saturated conditions were more favorable for lateral root growth than inundated conditions.

As evident in Table 4, the proportion of total root length per diameter class exhibited significant treatment effects. Although significant differences were observed for each classification interval, perhaps the most interesting effect was that a greater proportion of roots in the 1.0 – 1.5 mm diameter class were associated with inundated conditions. Otherwise, regardless of nutrient regime, the largest proportion of total root length fell in the 0.0 – 0.5 mm class. In regards to total root volume per root diameter class (Table 5), significant differences were observed with

respect to the proportion of total root volume per diameter class (1.5 – 2.0 mm) as well as in accordance with the hydrologic regime. With respect to the saturated treatments, a greater proportion of total root volume was associated with the 1.5 – 2.0 mm root diameter class, whereas for inundated treatments a greater proportion of total root volume was associated with the 1.0 – 1.5 mm root diameter class. Overall, there was a trend for larger diameter roots when inundation prevailed.

Experiment-1 demonstrated that optimum hydrologic conditions as well as an optimum range of nutrient availability do exist for *P. hemitomon* growth of the type desired for floating marsh creation purposes. An increase in the nitrogen loading rate from 25 to 50 g N m^{-2} yr^{-1} was sufficient to lead to significant increases in both above- and belowground production. Aboveground biomass was significantly greater under high nitrogen availability, whereas the influence of phosphorous was less evident. The positive response of aboveground production to elevated nitrogen availability was not surprising because nitrogen-limitation is known to negatively affect stem and leaf production in other grass species (Chapin et al. 1986; Di Tomasso and Aarsen 1989). Determining the influence of nutrient availability on belowground root and rhizome production is often difficult to generalize because belowground responses vary widely across and within plant taxonomic groups (de Kroon and Visser 2003). Additionally, soil heterogeneity and the spatial and temporal variability of sub-aerial nutrient resources differentially influence root system morphology (de Kroon and Visser 2003).

Table 4. The effect of manipulated nutrient availability and hydrology on the proportion of P. hemitomon total root length per root diameter class associated with Experiment-1.v2. All measurements were performed on live root tissue sampled immediately prior to experimental harvest. Values are means ± SE (n = 5).

	Root diameter classes (mm)			
Treatment	0.0 – 0.5	0.5 – 1.0	1.0 – 1.5	1.5 – 2.0
N,P (s)	0.80±.033[a]	0.05±.028 [a]	0.12±.019[ba]	0.03±.010[dc]
N,P (i)	0.72±.035[a]	0.09±.021[ba]	0.15±.037[ba]	0.03±.008[bdac]
NN,P (s)	0.80±.017[a]	0.04±.008[ba]	0.08±.019[b]	0.08±.012[a]
NN,P (i)	0.74±.014[a]	0.09±.012[ba]	0.15±.008[ba]	0.02±.005[d]
N,PP (s)	0.81±.022[a]	0.02±.005[b]	0.08±.018[b]	0.07±.004[ba]
N,PP (i)	0.70±.033[a]	0.05±.009[ba]	0.21±.034[a]	0.03±.009[bdc]
NN,PP (s)	0.79±.014[a]	0.04±.005[ba]	0.10±.024[b]	0.06±.013[bac]
NN,PP (i)	0.72±.032[a]	0.10±.014[ba]	0.16±.028[ba]	0.02±.005[dc]
F – value $_{(df\ 7,32)}$	2.80[*]	3.59[*]	3.18[*]	6.00[**]

[a] Means with the same letter in the same column are not statistically different ($p < 0.05$) based on Tukey's multiple comparison procedure for all possible pairwise comparisons.
[**] Highly significant difference ($p < 0.01$); [*] significant difference ($p < 0.05$).

Table 5. The effect of manipulated nutrient availability and hydrology on the proportion of P. hemitomon total root volume per root diameter class associated with Experiment-1.v2. All measurements were performed on live root tissue sampled immediately prior to experimental harvest. Values are means ± SE (n = 5)

	Root diameter classes (mm)			
Treatment	0.0 – 0.5	0.5 – 1.0	1.0 – 1.5	1.5 – 2.0
N,P (s)	0.08±.006[a]	0.10±.028 [a]	0.55±.085[ba]	0.21±.069[dc]
N,P (i)	0.07±.012[a]	0.13±.040[ba]	0.50±.095[ba]	0.20±.061[bdac]
NN,P (s)	0.08±.010[a]	0.04±.014[ba]	0.35±.056[b]	0.44±.076[a]
NN,P (i)	0.08±.006[a]	0.14±.017[ba]	0.57±.048[ba]	0.13±.036[d]
N,PP (s)	0.06±.007[a]	0.02±.003[b]	0.33±.049[b]	0.46±.054[ba]
N,PP (i)	0.06±.012[a]	0.09±.027[ba]	0.62±.055[a]	0.16±.041[bdc]
NN,PP (s)	0.07±.005[a]	0.04±.004[ba]	0.40±.109[b]	0.38±.071[bac]
NN,PP (i)	0.08±.017[a]	0.14±.022[ba]	0.53±.054[ba]	0.18±.027[dc]
F – value$_{(df\ 7,32)}$	0.57[NS]	2.78[*]	2.08[NS]	5.41[**]

[a] Means with the same letter in the same column are not statistically different ($p < 0.05$) based on Tukey's multiple comparison procedure for all possible pairwise comparisons.
[**] Highly significant difference ($p < 0.01$); [*] significant difference ($p < 0.05$); [NS] non-significant difference ($p > 0.05$).

Plants in general respond to insufficient nutrient availability or nutrient stress via compensatory changes such as increased root absorption capacity for limiting nutrients, increased root:shoot ratio, or decreased photosynthetic output (Chapin et al. 1986). Net CO_2 assimilation associated with Experiment-1.v2 exhibited significant treatment effects, with greater rates associated with high nitrogen availability and saturated conditions, and lower rates associated with low nitrogen availability and inundated conditions. The decrease in net CO_2 assimilation rates under more stressful conditions supports findings described by Chapin et al. (1986). Moreover, such effects are likely to be exacerbated by inadequate nutrient absorption associated with site infertility or insufficient root biomass. It seems that the relative absence of root biomass observed under inundated hydrologic conditions not only affected nutrient absorption, but also lead to concordant decreases in net CO_2 assimilation. Both appear to be a result of the interactive effects of flooding stress and insufficient nitrogen acquisition and assimilation.

Photosynthetic nitrogen-use efficiency (PNUE), the photosynthetic rate expressed per unit nitrogen, provides a reliable measure of how efficiently available nitrogen is being utilized (Lambers et al. 1998). It is generally accepted for most plant species that as nitrogen availability and uptake increases, nitrogen use-efficiency decreases (Crawley 2005). Distinct or significant differences in *P. hemitomon* PNUE were not observed with respect to nitrogen availability, although there was a distinctive trend observed in Experiment-1.v1 for decreased PNUE under high nitrogen (and low phosphorous) conditions. However, this trend was not observed in Experiment-1.v2.

Root systems of monocotyledons, particularly grasses like *P. hemitomon*, tend to be extremely dense and fibrous, so much so that a primary tap root is generally indistinguishable from lateral roots (de Kroon and Visser 2003). Such root systems are also characterized by many lateral roots, none of which tend to be very large (≥ 5 mm) in diameter (Weaver 1968; de Kroon and Visser 2003). These traits were obvious upon close inspection of *P. hemitomon* roots analyzed in this study. *P. hemitomon* grown under elevated nitrogen availability concentrated a substantial amount of root biomass, particularly fine root biomass, in the upper portion of the vegetated mat, a trait common among monocots, although usually in relation to upper soil layers of terrestrial settings (Kutschera and Lichtenegger 1992). Whereas the surface layers were dominated by fine root material in Experiments 1, larger diameter coarse root material dominated at depth in the vegetated mat and in the water column directly beneath the vegetated mat. A substantial amount of root material was also associated with laterally-growing rhizomes, a characteristic that Kutschera and Lichtenegger (1992) and Hook et al. (1994) also associate with monocots. Because rhizome growth generally occurs in a lateral fashion it seemed appropriate to interpret it is as lateral spreading potential. Robust lateral growth not only has implications for greater created mat structural integrity, but may also contribute to overall mat buoyancy through gas trapping in inter-nodal spaces.

It was suggested by Brouwer (1963) that roots receive a disproportionate amount of the available soil nutrient pool because of their direct contact with the soil matrix. Consequently, roots tend to grow more rapidly than shoots until the associated nutrient:carbohydrate ratio increases to the point that carbohydrate supply limits growth. When this happens stems and leaves grow disproportionately because of their association with photosynthetically-derived carbohydrates (Brouwer 1963). In Experiment-1 *P. hemitomon* responded favorably to increased nitrogen availability with increased root and rhizome production, increased stem and leaf production, and the increased net CO_2 assimilation discussed earlier. Considering this, it seems that within the range of the nutrient loading rates applied here that *P. hemitomon* nutrient utilization was such that all biomass components benefited or at least exhibited notable increases over time. These rates were also sufficient to moderately affect allocation patterns as evidenced by shifts in the root:shoot ratio, although it is unclear whether or not such small shifts are ecologically significant or significant with respect to marsh creation.

Because floating marsh buoyancy is predominantly driven by *P. hemitomon* root and rhizome production, it was necessary to identify those nutrient conditions that would result in the greatest belowground production. Because a significant proportion of a floating marsh root mat is suspended in three-dimensional space beneath the surface of the water, it seemed particularly relevant to quantify root volume in addition to total root biomass. Because both root mass and root volume responded negatively to inundated conditions, it seems clear that such conditions should be avoided if creation is to be achieved in the most successful way possible. Alternatively, root mass and root volume responded positively to elevated nitrogen availability, but whether or not such loading rates can be effectively applied in a field setting demands further study.

The relative partitioning of biomass into either above- or belowground components was an integral aspect of Experiment-1 because enhanced aboveground production generally occurs at the expense of belowground production (Iwasa and Roughgarden 1984; Fitter 2005). Therefore,

it is important to recognize that although above- and belowground production responded favorably to elevated nitrogen availability, a substantially greater aboveground response relative to belowground response may not be desirable from a floating marsh creation perspective because of issues associated with mat structural integrity and buoyancy. Such shifts in allocation were, in fact, observed in this study and it is important to note that *P. hemitomon* root:shoot ratio decreased when both nitrogen and phosphorous availability increased. Despite a smaller root:shoot ratio and more equal biomass partitioning, significantly more root biomass was produced under high nitrogen availability. Whether such changes would ultimately impair the buoyancy and sustainability of vegetated mats in the long term is not known, and conducting an accurate assessment of short-term buoyancy was not feasible in Experiment-1. For this reason root specific gravity was assessed.

Inundated conditions negatively affected all aspects of *P. hemitomon* growth response. Submergence, or in this case inundation, is recognized as a plant stressor even for wetland-adapted species (Jackson 1990; Blom et al. 1996; Jackson and Armstrong 1999). Experiment-1. demonstrated that *P. hemitomon* above- and belowground production, rhizome length, and root volume were all significantly less when inundated conditions prevailed. Moreover, root:shoot ratio was also influenced by the hydrologic regime. Although not a major facet of this study, mean stem height associated with Experiment-1.v2 was also significantly greater when inundated conditions prevailed. Such effects have been documented in numerous wetland-adapted plant species (Sasser 1994; Vartapetian and Jackson 1997; Willis and Hester 2004). Stem elongation brings a larger proportion of the aboveground biomass above the surface of the water where access to photosynthetically active radiation is greater (Jackson 1990; Laurentius et al. 1996). Responses to inundated conditions such as stem elongation, reduced root production, and decreased root:shoot ratio are not necessarily desirable from a floating marsh creation perspective. Therefore, structural designs and plant establishment techniques that fail to minimize inundation should generally be avoided.

Experiment-2: Evaluating the effects of substrate type

P. hemitomon aboveground biomass associated with Experiment-2.v1 (Figure 24) exhibited a highly significant treatment effect ($F_{11,48} = 7.67$; $p < 0.0001$), as did total belowground biomass or amount change ($F_{11,48} = 7.67$; $p < 0.0001$). Plants grown in conjunction with peat or peat-containing substrate materials were associated with greater above- and belowground biomass.

Although not necessarily harvested biomass, loss of mass due to decomposition associated with Experiment-2.v2 (Figure 25) varied significantly across treatment ($F_{8,44} = 725.98$; $p < 0.0001$), ranging from a minimum of 25.5 g (sugarcane leaf stripping) to a maximum of 82.0 g (hardwood mulch). Dry mass loss values associated with the water-only control (C – 1) represents airborne particulate deposition. All other treatments were adjusted by this amount.

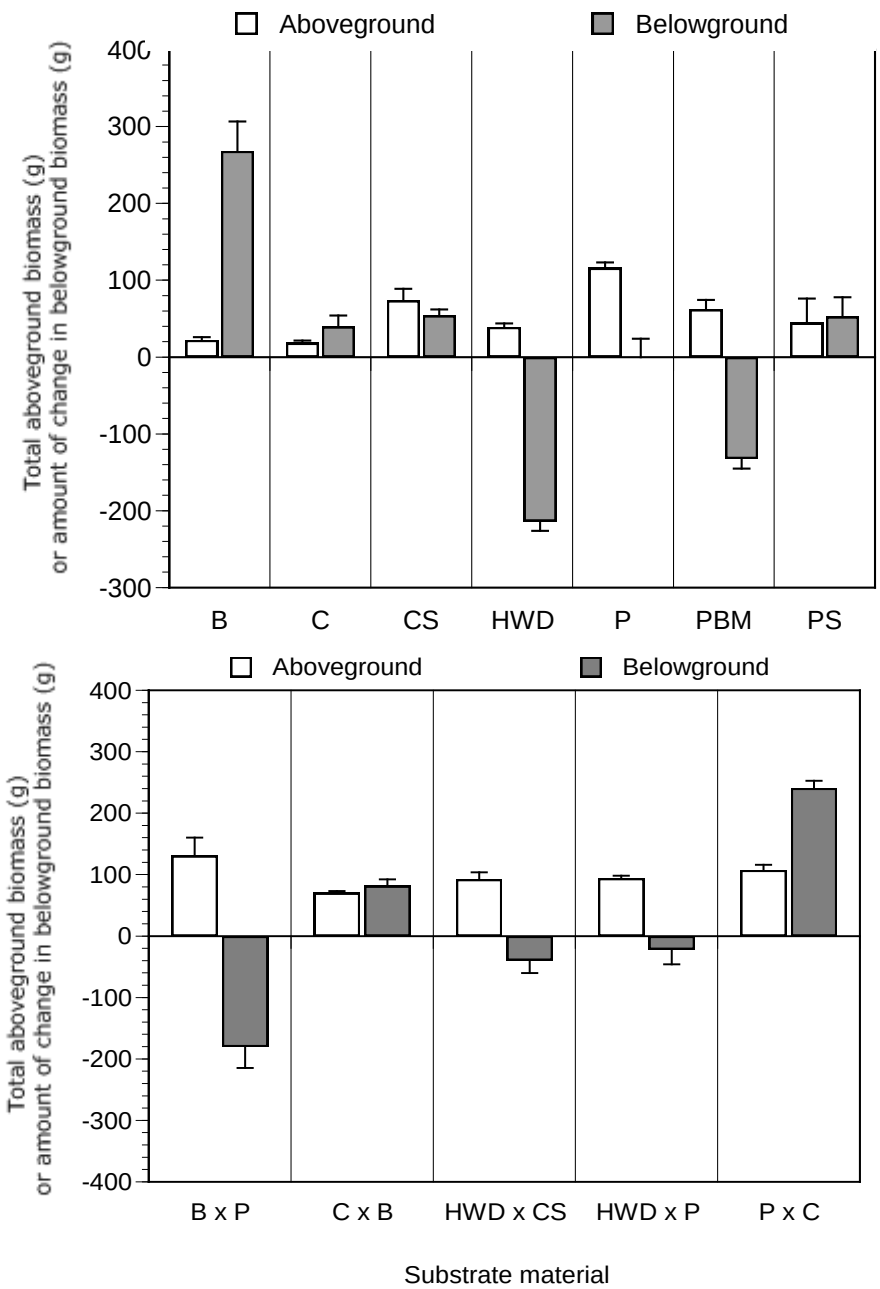

Figure 24. The effect of individual (top panel) and blended (bottom panel) substrate material on *P. hemitomon* total biomass (g) associated with Experiment-2.v1, measured as dry biomass for aboveground biomass and as amount change for belowground biomass. Treatment codes are as follows: B = bagasse; C = cypress mulch; CS = sugarcane leaf strippings; HWD = hardwood mulch; P = peat; PBM = pine bark mulch; PS = pine shavings. Values are means ± SE (n = 5).

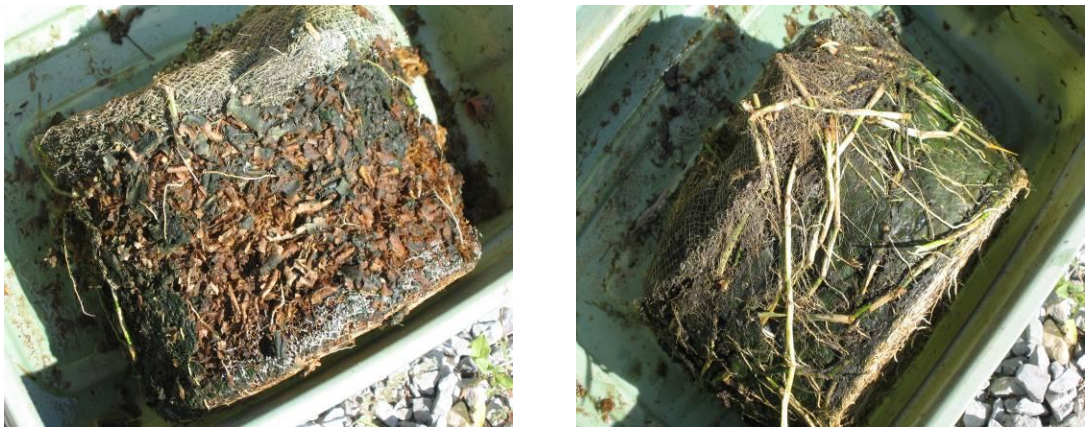

Illustration 17. Effect of substrate material on root and rhizome production. Left frame is a pine shaving treatment and right frame is a sphagnum peat treatment.

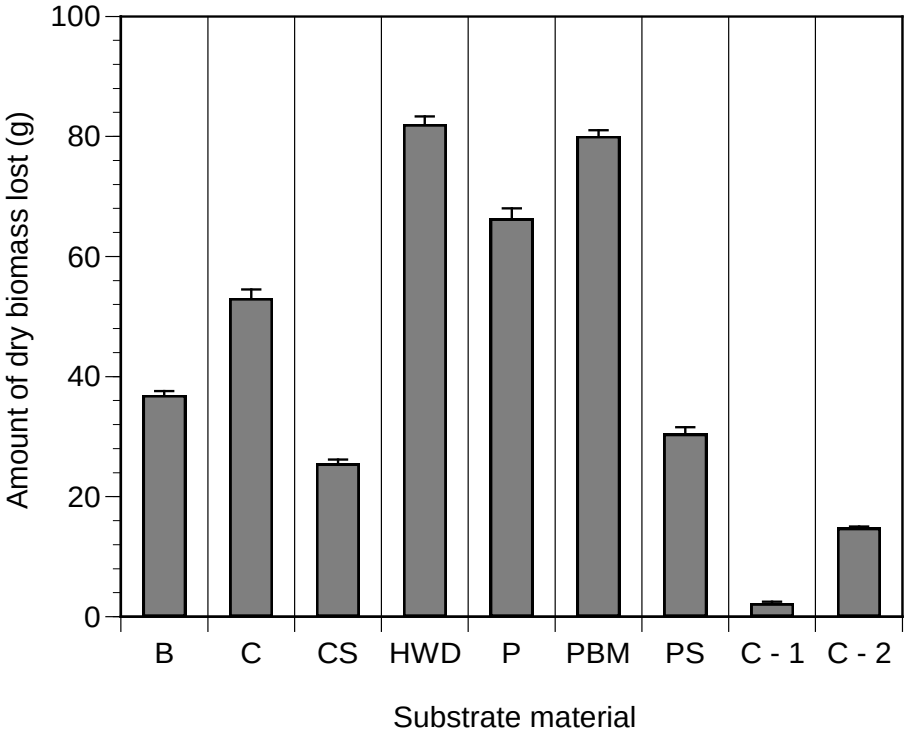

Figure 25. The effect of substrate material on amount of dry biomass lost to decomposition in Experiment-2.v2. Treatment codes are as follows: B = bagasse; C = cypress mulch; CS = sugarcane leaf strippings; HWD = hardwood mulch; P = peat; PBM = pine bark mulch; PS = pine shavings; C – 1 = tap water; C – 2 = tap water with Duralast coconut fiber. Values are means ± SE (n = 5).

P. hemitomon cumulative stem height associated with Experiment-2.v1 (Figure 26) exhibited a highly significant main effect of time (Wilk's lambda: $F_{9,40} = 116.92$; $p < 0.0001$) and a significant time by treatment interactive effect (Pillai's trace: $F_{99,432} = 1.72$; $p < 0.0001$). Overall, cumulative stem height was greatest for those plants grown in peat and peat-containing substrate materials.

Total stem number, total stem height, and mean stem height associated with Experiment-2.v1 (Table 6) were assessed in August 2005 during the final round of sequential aboveground sampling. Considering the significant differences observed previously with respect to cumulative stem height, it is not surprising that total stem number ($F_{11,48} = 5.88$; $p < 0.0001$), total stem height ($F_{11,48} = 6.06$; $p < 0.0001$), and mean stem height ($F_{11,48} = 7.27$; $p < 0.0001$) all exhibited highly significant differences with respect to substrate material. Generally, each of these stem metrics were greatest for those plants grown in conjunction with peat and peat-containing substrate materials.

P. hemitomon net CO_2 assimilation associated with Experiment-2.v2 (Figure 27) assessed at peak standing crop in July of 2005 did not exhibit a significant treatment effect ($F_{11,48} = 0.77$; $p = 0.6715$). Similarly, tissue nitrogen content (Figure 28) failed to exhibit a significant treatment effect ($F_{11,48} = 1.38$; $p = .2135$). Photosynthetic nitrogen-use efficiency or PNUE (Figure 28) followed suite in that it did not exhibit a significant treatment effect either ($F_{11,48} = 1.05$; $p = 0.4212$). No particularly revealing trends or treatment effects were evident for either variable.

Substrate redox potential associated with Experiment-2.v1 (Figure 29), measured over the course of the experiment, exhibited a significant main effect of time (Wilk's lambda: $F_{5,44} = 136.04$; $p < 0.0001$), as well as a significant time by treatment interactive effect (Pillai's trace: $F_{55,240} = 1.47$; $p < 0.0257$). As expected when flooded or inundated conditions prevail, substrate redox potential decreased over time in nearly all treatments.

Chemical oxygen demand (COD) was of concern in regards to substrate decomposition, although it was doubtful that COD would be as much of an issue in a field setting where a stagnant hydrology is less likely to occur. COD, the amount of oxygen required to chemically oxidize a specific quantity of organic matter, is also associated with oxygen stress or hypoxia, a condition that is ubiquitous under semi- to permanently flooded conditions. In aquatic environments COD and biological oxygen demand (BOD) are related, with COD generally exceeding BOD (APHA 1989). Clearly then, with particular relevance to aspects of this study, there was the potential for COD to negatively affect *P. hemitomon* growth response via the intensification of already stressful hypoxic conditions. Although all substrates evaluated here were plant-derived materials, it was expected that each would possess different structural and chemical qualities that would differentially affect the inherent rooting environment. Substrate COD, measured sequentially over the 20 week course of Experiment-2.v2 (Figure 30), exhibited a highly significant main effect of time (Wilks' lambda: $F_{3,34} = 1388.25$; $p < 0.0001$) as well as a highly significant time by treatment interactive effect (Pillai's trace: $F_{24,99} = 10.73$; $p < 0.0001$). Interestingly, COD varied by treatment for the first few sampling periods, but with time differences ameliorated to the point that no significant treatment effects were observed at completion (week-20).

Table 6. The effect of substrate material on P. hemitomon total stem number, total stem height (cm), and mean stem height (cm), all measured at harvest after 9 months of growth. Inundated conditions (flooded to a depth of 10 cm above the base of all stems) were maintained over the course of the experiment. All values were determined at harvest. Values are means ± SE (n = 5).

Substrate material	Total stem number	Total stem height (cm)	Mean stem height (cm)
Bagasse	25.0±5.2[d]	970.2±198.3[c]	40.0±3.1[ebdc]
Cypress mulch	24.8±5.8[d]	954.14±211.9[d]	39.2±2.6[edc]
Sugarcane leaf strippings	54.0±10.7[bdac]	2730.7±598.5[bac]	49.0±3.6[bdac]
Hardwood mulch	40.4±2.9[bdc]	1728.9±172.3[bc]	42.6±1.6[ebdac]
Peat	74.8±3.5[ba]	4010.7±146.2[ba]	53.8±1.6[a]
Pine bark mulch	68.2±9.1[bac]	3177.2±605.6[bac]	45.5±2.6[ebdac]
Pine shavings	41.0±16.4[bdc]	1858.3±1077.4[bc]	36.8±5.4[ed]
Bagasse and Peat	84.0±14.7[a]	4663.7±1006.0[a]	54.4±2.0[a]
Cypress mulch and Bagasse	27.8±2.9[dc]	963.1±140.7[c]	34.0±1.8[e]
Sugarcane leaf strippings and Hardwood mulch	64.6±10.8[bdac]	3189.0±532.4[bac]	49.3±1.3[bdac]
Hardwood mulch and Peat	60.0±3.8[bdac]	3158.7±169.7[bac]	52.8±1.1[bac]
Peat and Cypress mulch	76.6±2.4[ba]	4095.5±168.2[ba]	53.5±1.9[ba]
F – value $_{(df\ 11,48)}$	5.88**	6.06**	7.27**

[a] Means with the same letter in the same column are not statistically different ($p < 0.05$) based on Tukey's multiple comparison procedure for all possible pairwise comparisons.
** Highly significant difference ($p < 0.01$).

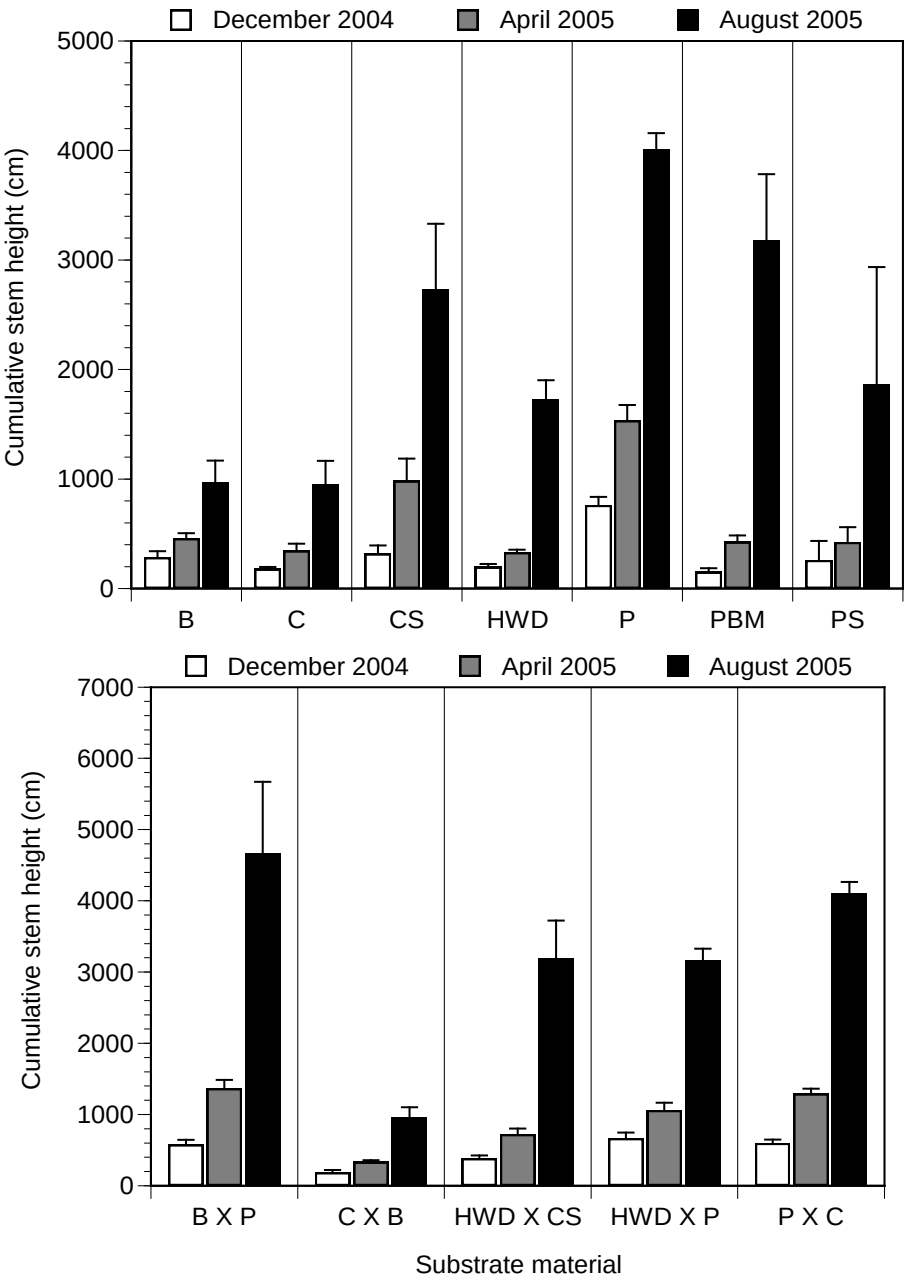

Figure 26. The effect of individual (top panel) and blended (bottom panel) substrate material on *P. hemitomon* cumulative stem height (cm) associated with Experiment-2.v1, measured monthly over a 9-month period. Treatment codes are as follows: B = bagasse; C = cypress mulch; CS = sugarcane leaf strippings; HWD = hardwood mulch; P = peat; PBM = pine bark mulch; PS = pine shavings. Values are means ± SE (n = 5).

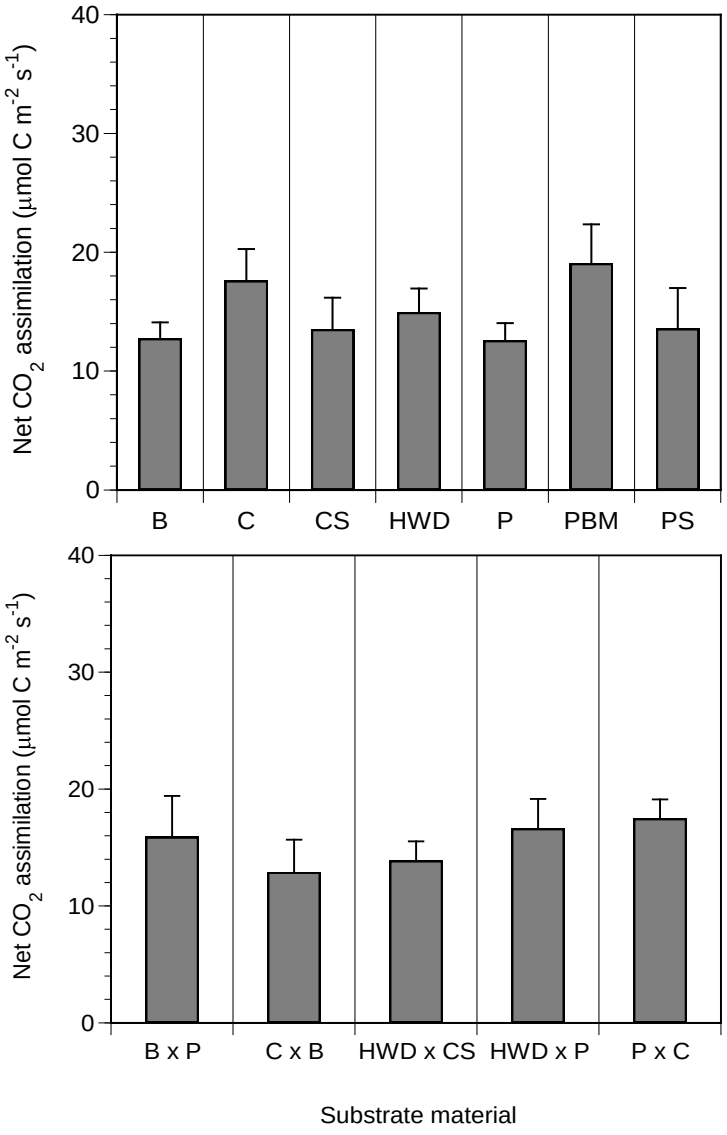

Figure 27. The effect individual (top panel) and blended (bottom panel) substrate material on *P. hemitomon* net CO_2 assimilation rate (µmol C m^{-2} s^{-1}) associated with Experiment-2,v2. Treatment codes are as follows: B = bagasse; C = cypress mulch; CS = sugarcane leaf strippings; HWD = hardwood mulch; P = peat; PBM = pine bark mulch; PS = pine shavings; B x P = bagasse and peat; C x B = cypress mulch and peat; HWD x CS = hardwood mulch and sugarcane leaf strippings; HWD x P = hardwood mulch and peat; P x C = peat and cypress mulch. Values are means ± SE (n = 5).

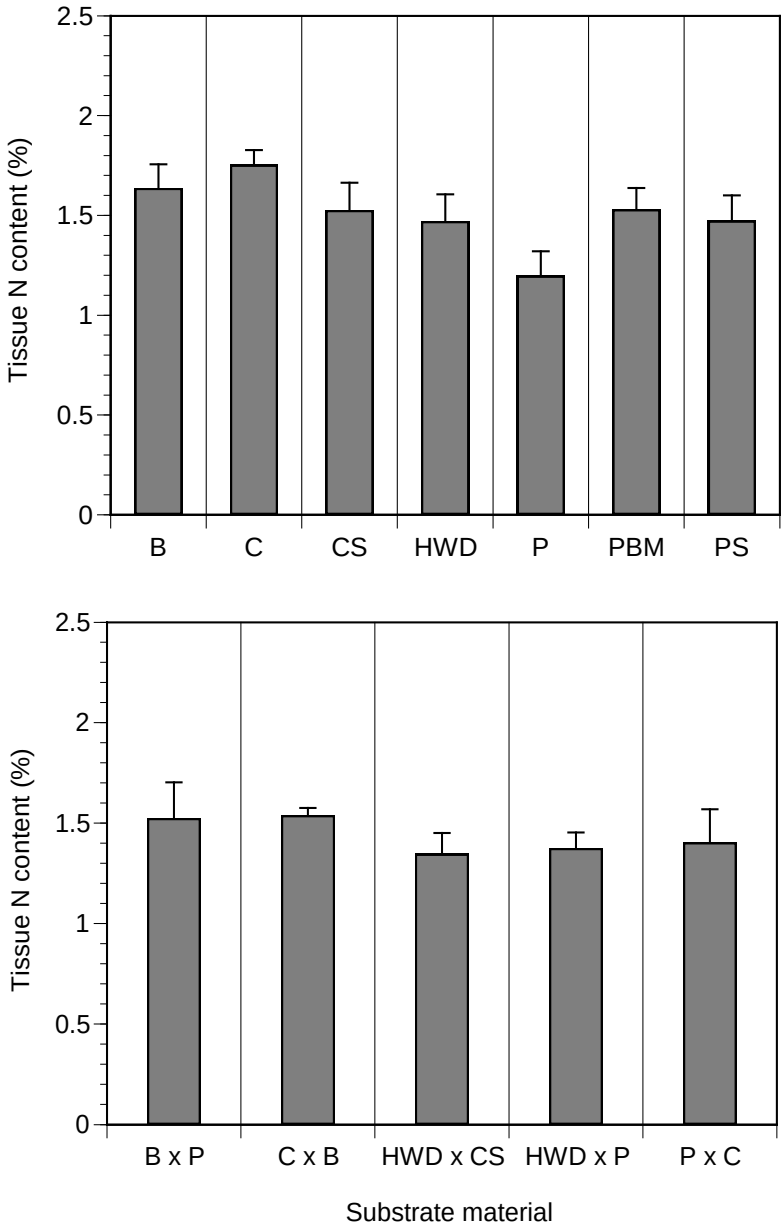

Figure 28. The effect of individual (top panel) and blended (bottom panel) substrate material on *P. hemitomon* tissue nitrogen content (%) associated with Experiment-2.v1. Treatment codes are as follows: B = bagasse; C = cypress mulch; CS = sugarcane leaf strippings; HWD = hardwood mulch; P = peat; PBM = pine bark mulch; PS = pine shavings; B x P = bagasse and peat; C x B = cypress mulch and peat; HWD x CS = hardwood mulch and sugarcane leaf strippings; HWD x P = hardwood mulch and peat; P x C = peat and cypress mulch. Values are means ± SE (n = 5).

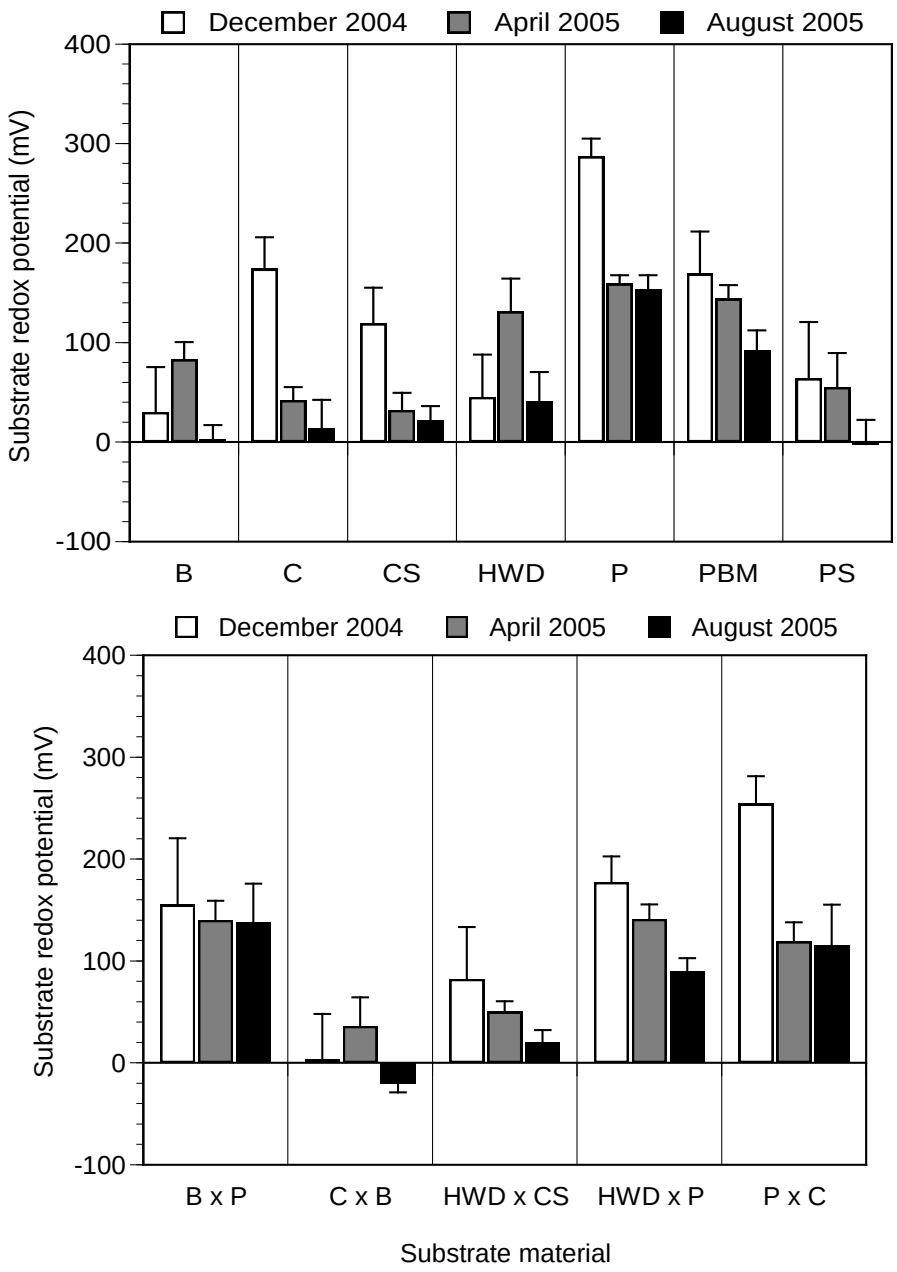

Figure 29. The effect of individual (top panel) and blended (bottom panel) substrate material on substrate redox potential (mV) associated with Experiment-2, measured monthly over a 9-month period at an approximate depth of 10 cm. Treatment codes are as follows: B = bagasse; C = cypress mulch; CS = sugarcane leaf strippings; HWD = hardwood mulch; P = peat; PBM = pine bark mulch; PS = pine shavings. Values are means ± SE (n = 5).

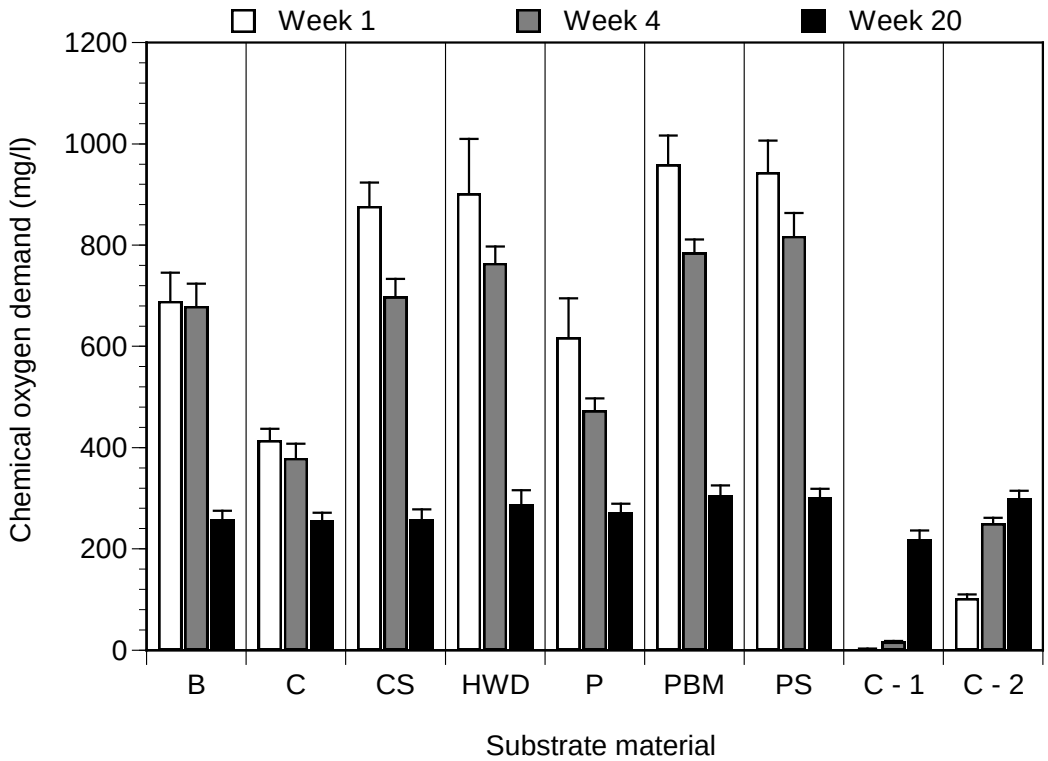

Figure 30. The effect substrate material on interstitial chemical oxygen demand (mg/l), measured using interstitial water withdrawn from a depth of approximately 10 cm. Treatment codes are as follows: B = bagasse; C = cypress mulch; CS = sugarcane leaf strippings; HWD = hardwood mulch; P = peat; PBM = pine bark mulch; PS = pine shavings; C – 1 = tap water; C – 2 = tap water with Duralast coconut fiber. Values are means ± SE (n = 5).

Plant growth and vigor, as well as the partitioning of biomass to above- and belowground components, is directly influenced not only by the corresponding light and moisture regime, but by characteristics inherent in the surrounding substrate material (Chapin 1980; Lambers et al. 1998). Significant differences in *P. hemitomon* growth and vigor were observed across the suite of substrate materials tested in Experiment-2.v1. *P. hemitomon* aboveground production, including total stem number, total stem height, and mean stem height were all greater in the presence of peat or peat-containing substrate materials. The same substrate materials also tended to be associated with less reduced or less hypoxic conditions. Soils may become hypoxic within hours after flooding because oxygen consumption belowground occurs at very high rates. Plants roots typically respire at rates faster than shoots (Amthor 1989), although soil microbial respiration rates are faster still (Paul and Clark 1996). Such oxygen demands are further compromised by the slow diffusion of oxygen in aqueous solutions, at times 10^{-4} the rate as through air-filled pores (Epstein and Bloom 2005). Reduced or oxygen-limited conditions incur stress for both terrestrial and wetland-adapted species; wetland species just possess adaptations for tolerating higher levels of these stressors. However, such stressors may at least partially explain the poor performance of plants grown in non-peat-containing substrate materials.

Furthermore, substrates that were indicative of more reduced conditions were also associated with greater chemical oxygen demand (COD). Chemical oxygen demand, particularly in wetland soils, is interrelated with redox potential in that higher COD values equate to less biologically available oxygen and therefore a greater potential for oxygen deficiency (Gambrell and Patrick 1978; Richardson and Vepraskas 2001). Those substrate materials that were most favorable for *P. hemitomon* growth were associated with low COD values and less reduced conditions.

Epstein and Bloom (2005) provide some insight into several of the substrate materials tested here in terms of general characteristics. They suggest that peat is generally acidic, known to release organic substances over time, and is overall beneficial for ion exchange. Bark on the other hand, regardless of whether conifer and hardwood-derived, has low water-holding capacity, immobilizes nitrogen and must be aged to diminish toxic content. Sawdust, represented in this study by pine shavings, is generally associated with poor nutrient content and, depending on source, alkaline pH (Epstein and Bloom 2005). In reference to sugarcane leaf strippings and to a lesser degree bagasse, it is common in intensively farmed agricultural settings in Louisiana for sugarcane to be sprayed with defoliating compounds such as PALADO-L (Monsanto Company, St. Louis, MO), a glyphosate ripening agent (LSU AgCenter 2001). While no definite confirmation underlies this assertion, if fields where sugarcane leaf strippings were obtained were sprayed, it is possible that PALADO-L residues were still present and may have at least partially explained the poor *P. hemitomon* growth response associated with this treatment.

Experiment-3: Evaluating the effects of mat type on vegetation establishment

P. hemitomon above- and belowground biomass associated with Experiment-3.v1 (Figure 31) both exhibited highly significant treatment effects ($F_{4,20} = 7.67$; $p < 0.0001$ and ($F_{4,20} = 3.52$; $p = 0.0250$ respectively). Overall, *P. hemitomon* aboveground production responded rather uniformly to mat or containment material, as did belowground production, the exception being those plants grown in conjunction with shredded birch.

P. hemitomon cumulative stem height exhibited a highly significant main effect of time (Wilk's lambda: $F_{2,19} = 554.6$; $p < 0.0001$), as well as a highly significant time by treatment interactive effect (Pillai's trace: $F_{8,40} = 5.33$; $p < 0.0001$). The most notable difference was decreased cumulative stem height exhibited by plants grown in conjunction with shredded birch, whereas those grown in conjunction with all other mat or containment materials exhibited rather uniform cumulative stem height (Figure 32). Total stem number ($F_{4,20} = 9.71$; $p < 0.0001$), cumulative stem height ($F_{4,20} = 19.26$; $p < 0.0001$), and mean stem height ($F_{4,20} = 7.12$; $p < 0.0001$) associated with Experiment-3.v1 also varied according to treatment (Table 7). As observed with respect to cumulative stem height, those plants grown with shredded birch also exhibited fewer and shorter stems.

Substrate redox potential associated with Experiment-3.v1 (Figure 33), which was measured bimonthly over the course of the experiment, exhibited a non-significant main effect of time (Wilks' Lambda $F_{1,20} = 0.77$; $p = 0.3913$) but a significant time by treatment interactive effect (Wilks' Lambda $F_{4,20} = 5.75$; $p = 0.0030$). Although statistically significant, no particularly revealing trends were observed.

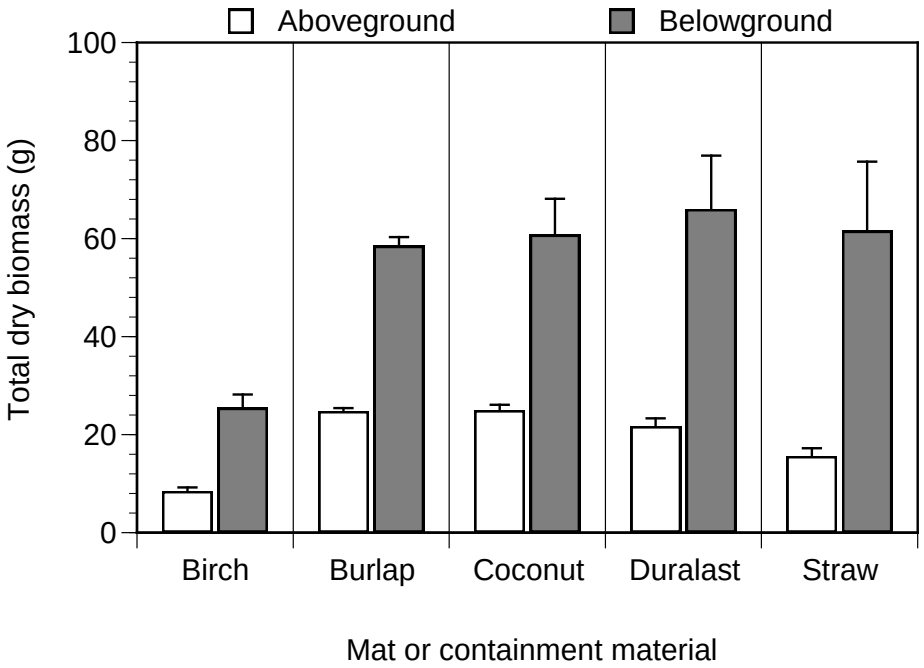

Figure 31. The effect of mat or containment material on *P. hemitomon* above- and belowground dry biomass (g) associated with Experiment-3.v1. Values are means ± SE (n = 5).

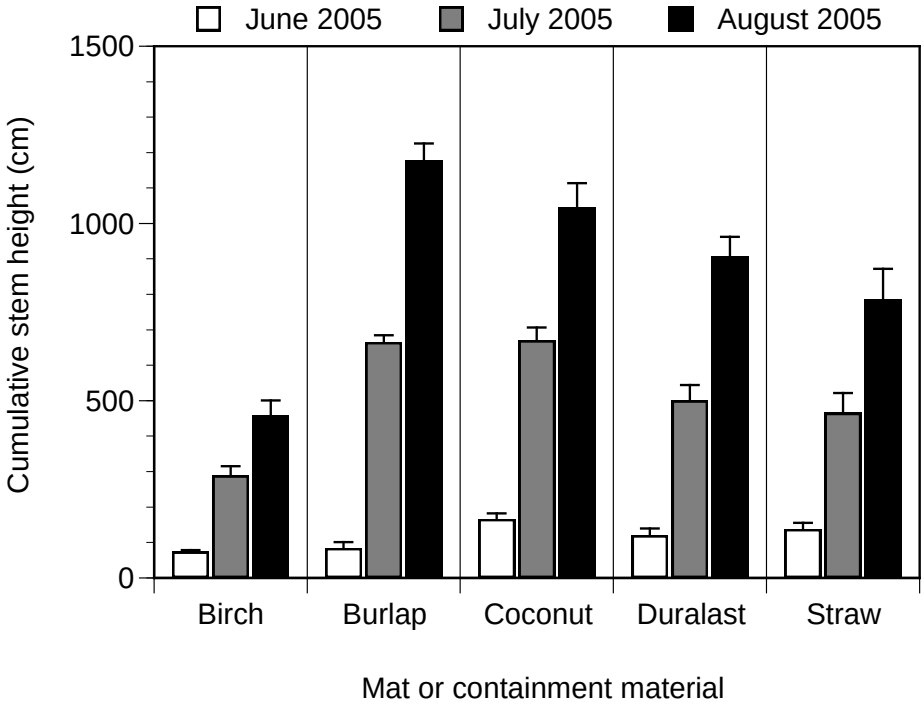

Figure 32. The effect of mat or containment material on *P. hemitomon* cumulative stem height (cm) associated with Experiment-3.v1, measured monthly over a 3-month period. Values are means ± SE (n = 5).

Table 7. The effect of mat or containment material on P. hemitomon total stem number, total stem height (cm), and mean stem height (cm) associated with Experiment-3.v1, measured at harvest after 3 months of growth. Inundated conditions (flooded to a depth of 10 cm above the base of all stems) were maintained over the course of the experiment. All values were determined at harvest. Values are means ± SE (n = 5).

Mat or containment material	Total stem number	Cumulative stem height (cm)	Mean stem height (cm)
Birch	15.4±1.63[c]	457.2±43.43[c]	29.9±1.29[b]
Burlap	34.2±2.51[a]	1177.0±48.62[a]	34.7±1.07[a]
Coconut	28.4±2.65[ba]	1044.1±69.84[ba]	37.1±1.14[a]
Duralast	24.6±1.40d[bc]	908.34±53.67[b]	36.9±0.68[a]
Straw	23.2±2.57b[bc]	784.2±87.77[b]	33.9±1.15[ba]
F – value $_{(df\ 4,20)}$	9.71**	19.26**	7.12**

[a] Means with the same letter in the same column are not statistically different ($p < 0.05$) based on Tukey's multiple comparison procedure for all possible pairwise comparisons.
** Highly significant difference ($p < 0.01$).

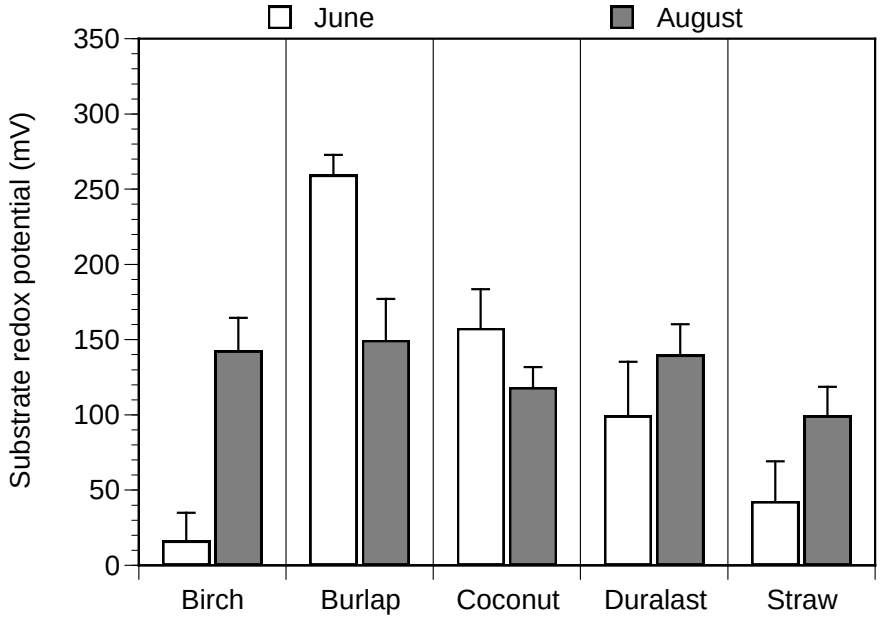

Figure 33. The effect of mat or containment material and peat substrate on substrate redox potential (mV) associated with Experiment-3.v1, measured at a depth of approximately 10 cm. Values are means ± SE (n = 5).

When *P. hemitomon* growth responses with respect to different mat or containment materials were evaluated, it is important to note that peat served as the sole substrate material for all experimental units. With the substrate material and nutrient regime uniform across treatments, all differences in plant response could be attributed to differential effects associated with each mat or containment material. *P. hemitomon* above- and belowground production was fairly uniform across four of the five mat or containment materials, the main exception being shredded birch, and to a lesser extent, straw. The birch substrate material, which appeared to be shredded birch wood may have a high C:N ratio as most wood fiber does (Barnes et al. 1998). A high C:N ratio has the potential to enhance nutrient limitation from the perspective of the corresponding plant because a greater proportion of the nutrient pool would be sequestered and utilized by the microbial community for organic matter decomposition, which may also cause a rapid decrease in redox potential (Barnes et al. 1998). However, it is also possible that birch wood possesses some chemical quality that negatively affects or suppresses plant growth.

Support structures that showed the best results in Experiment-3.v1, along with a hydroponic structure, were tested in Exeperiment-3.v2, with additional treatments. Total vegetative cover or the proportion of total area vegetated with respect Experiment-3.v2 (Figure 34) exhibited a highly significant main effect of time (Wilks' Lambda: $F_{2,17} = 62.03$; $p < 0.0001$) as well as a significant time by treatment interactive effect (Pillai's Trace: $F_{10,36} = 6.27$; $p < 0.0001$). *P. hemitomon* vegetative cover increased over time in the Duralast coconut fiber (PD), Duralast coconut fiber and humic acid amendment (PDH), and Duralast coconut fiber with canvas underpinning (PDC) treatments, whereas the proportion of total area vegetated did not exhibit noticeable change with respect to the chicken wire (PC), chicken wire with humic acid amendment (PCH), or Duralast coconut fiber and bagasse (PDB) treatments.

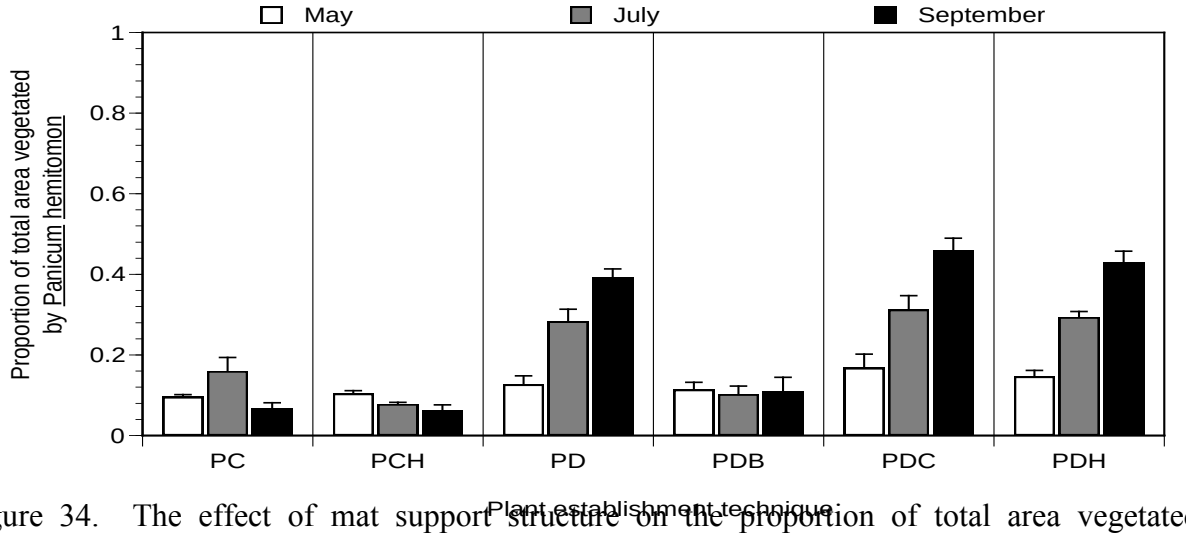

Figure 34. The effect of mat support structure on the proportion of total area vegetated, measured monthly over a 5-month period (Experiment-3.v2). Treatment codes are as follows: PC =Chicken wire; PCH = Chicken wire and humic acid amendment; PD = Duralast coconut fiber; PDB = Duralast coconut fiber and bagasse; PDC = Duralast coconut fiber with canvas underpinning; PDH = Duralast coconut fiber and humic acid amendment. Values are means ± SE (n = 4).

Illustration 18. Experiment-3.v2 showing belowground *P. hemitomon* root growth after 5 months of growth (treatment is PD). Note new rhizomes emerging from the bottom of the mat.

P. hemitomon aboveground biomass showed significant treatment effects with respect to Experiment-3.v2 (Table 8), which ranged from 20.2 g (PCH treatment) to 152.3 g (PDC treatment). *P. hemitomon* rhizome biomass associated with plant support structure also exhibited a significant treatment effect, in this case ranging from 9.1 g (PCH treatment) to 118.7 g (PDH treatment).

P. hemitomon total biomass, a collective measure including stems and leaves, rhizomes and roots, did exhibit a significant treatment effect across plant support structures (Figure 35; $F_{5,18} = 33.55$; $p < 0.0001$). *P. hemitomon* total biomass ranged from 49.8 g (PCH treatment) to 376.3 g (PDC treatment). This information can be used to determine the best methods for establishing plants for AFS's.

Table 8. P. hemitomon dry biomass values (g), partitioned by component, (stem/leaf, rhizome, and root contributions) for each of the plant support structures associated with Experiment 3-v2. Treatment codes: PC = Chicken wire; PCH = Chicken wire with humic acid amendment; PD = Duralast coconut fiber; PDB = Duralast coconut fiber with bagasse; PDC = Duralast coconut fiber with canvas underpinning; PDH = Duralast coconut fiber with humic acid amendment. Values are means ± SE (n = 4).

	P. hemitomon biomass (g)			
Treatment	stem/leaf	rhizome	root	total
PCH	20.2±4.54 [b]	9.1±1.9[b]	20.4±4.2[b]	49.8±21.17[a]
PC	23.2±5.58[b]	12.8±2.6[b]	20.7±5.1[b]	56.8±26.37[a]
PDB	28.6±6.0 [b]	22.4±8.8[ba]	32.0±12.6[b]	83.1±54.25[a]
PD	111.7±11.4[a]	101.9±9.02[a]	87.3±17.3[a]	300.9±37.46[b]
PDH	123.1±9.0[a]	118.7±4.23[a]	114.2±14.4[a]	356.1±47.38[b]
PDC	152.3±25.5[a]	101.6±13.4[a]	122.3±12.6[a]	376.3±98.79[b]
F – value $_{(df\ 6,21)}$	22.03[**]	42.58[**]	15.39[**]	33.55[**]

[a] Means with the same letter in the same column are not statistically different ($p < 0.05$) based on Tukey's multiple comparison procedure for all possible pairwise comparisons. [**] Highly significant difference ($p < 0.01$); [NS] non-significant difference ($p > 0.05$).

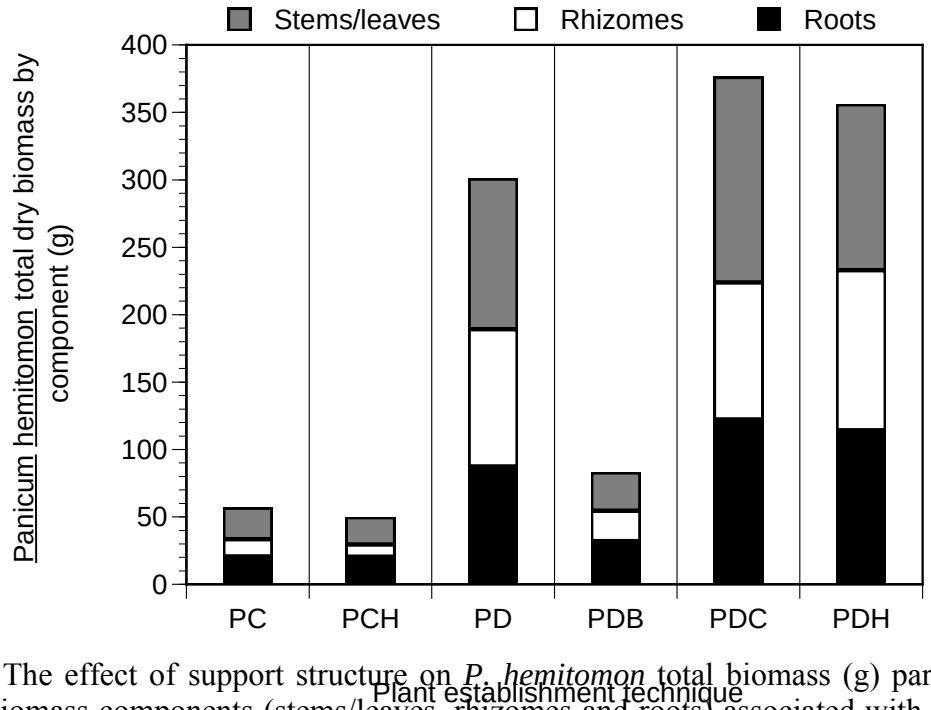

Figure 35. The effect of support structure on *P. hemitomon* total biomass (g) partitioned into individual biomass components (stems/leaves, rhizomes and roots) associated with Experiment-3.v2. Treatment codes are as follows: PC = Chicken wire; PCH = Chicken wire with humic acid amendment; PD = Duralast coconut fiber; PDB = Duralast coconut fiber with bagasse; PDC = Duralast coconut fiber with canvas underpinning; PDH = Duralast coconut fiber with humic acid amendment. Values are means ± SE (n = 4).

P. hemitomon total rhizome length (Table 9), measured using freshly-harvested rhizome material, varied significantly according to plant support structure ($F_{11,36}$ = 21.66; p < 0.0001). Rhizome length ranged from 4.7 cm (PCH treatment) to 56.7 cm (PDH treatment). A highly significant difference was also observed with respect to *P. hemitomon* estimated root volume ($F_{11,36}$ = 9.29; p < 0.0001). Estimated root volume ranged from 118.0 cm^3 (PCH treatment) to 706.0 cm^3 (PDC treatment).

P. hemitomon vegetative cover in relation to plant establishment technique exhibited several interesting trends. First there was an obvious grouping of treatments that performed well (PD, PDC, and PDH) and poorly-performing treatments (PC, PCH, PDB). Treatments that included Duralast coconut fiber as the mat or containment material and peat as the substrate material performed well, whereas poorly-performing treatments all lacked peat as a substrate, and only one (PDB) incorporated Duralast coconut fiber. Second, not only was *P. hemitomon* total cover in treatments that performed well significantly greater, but total vegetative cover among these treatments was relatively uniform. There was a trend for greater *P. hemitomon* total cover in the PDC and PDH treatments compared to that of the PD treatment, but total cover only represents

Table 9. P. hemitomon total rhizome length (cm) and estimated root volume (cm3) with respect to plant support structure associated with Experiment-3.v2. Treatment codes are as follows: PC = Chicken wire; PCH = Chicken wire with humic acid amendment; PDB = Duralast coconut fiber with bagasse; PDC = Duralast coconut fiber with peat and canvas underpinning; PDH = Duralast coconut fiber with peat and humic acid amendment. Values are means ± SE (n = 4).

Treatment	*P. hemitomon* total rhizome length (cm)	*P. hemitomon* estimated root volume (cm^3)
PC	5.7 ± 0.99^{f}	119.8 ± 29.88^{c}
PCH	4.7 ± 1.13^{f}	118.0 ± 24.83^{c}
PDB	10.7 ± 3.9^{f}	184.9 ± 72.90^{bc}
PDC	49.0 ± 4.08^{ba}	706.4 ± 73.04^{a}
PDH	56.7 ± 5.53^{a}	659.7 ± 83.70^{a}
F – value $_{(df\ 11,36)}$	21.66^{**}	9.29^{**}

[a] Means with the same letter in the same column are not statistically different ($p < 0.05$) based on Tukey's multiple comparison procedure for all possible pairwise comparisons.
** Highly significant difference ($p < 0.01$); NS non-significant difference ($p > 0.05$).

one measure of plant performance. Total cover should be interpreted collectively with other *P. hemitomon* growth metrics, such as root production and total rhizome length, as well as with total mat dry biomass. The positive influences of canvas underpinning and humic acid amendment on *P. hemitomon* growth (PDC and PDH treatments respectively) are promising and merit further evaluation.

Experiment-4: Evaluation of edge-expansion species

The proportion of total area vegetated for all multi-species treatments (Figure 36), which incorporated vegetative cover for *P. hemitomon* and each secondary species (–edge species") when present, exhibited a highly significant main effect of time (Wilks' Lambda: $F_{2,20} = 149.87$; $p < 0.0001$) as well as a highly significant time by treatment interactive effect (Pillai's Trace: $F_{12,42} = 4.74$; $p < 0.0001$). Note that the proportion of total area vegetated increased in nearly all treatments over the duration of the experiment, and had it not been for a moderate insect-induced defoliation event between months three and four, as well as the confining nature of the experimental vessels, it is likely that

Illustration 19. Experiment-4 showing aboveground growth of *P. hemitomon* after 4 weeks of growth.

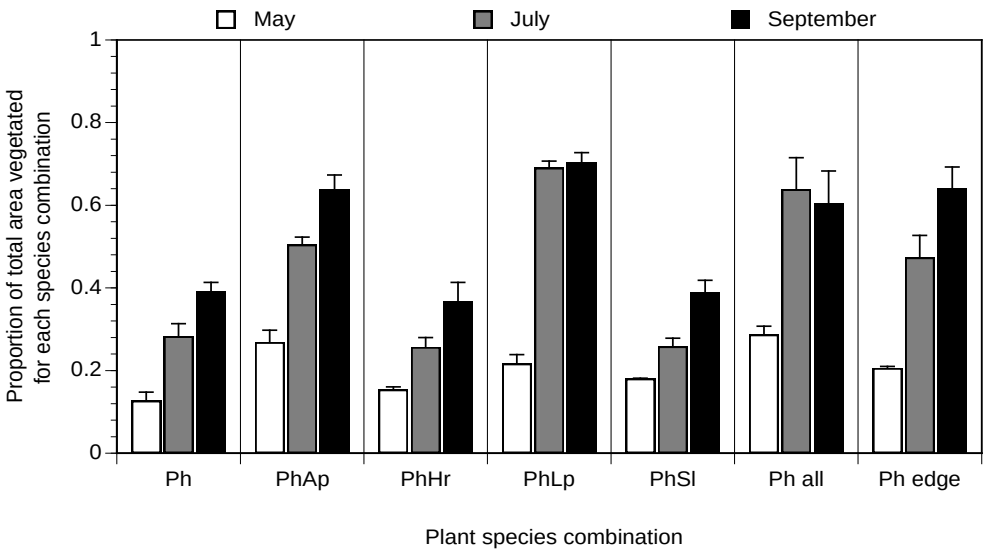

Figure 36. The effect of plant species combination on the proportion of total area vegetated, measured monthly over a 5-month period. Treatment codes are as follows: Ph = *P. hemitomon* only; PhAp = *P. hemitomon* with *A. philoxeroides*; PhHr = *P. hemitomon* with *H. ranunculoides*; PhLp = *P. hemitomon* with *L. peploides*; PhSl = *P. hemitomon* with *S. lancifolia*; Ph all = *P. hemitomon* with all species (including S. lancifolia); Ph edge = *P. hemitomon* with all edge species (excluding *S. lancifolia*). Values are means ± SE (n = 4).

treatments such as the *P. hemitomon* with *L. peploides* (PhLp) would have reached much greater vegetative cover. Interestingly, the greatest vegetative cover or proportion of total area vegetated was attained not by a treatment with the greatest number of species, but by a two-species combination. Vegetative cover associated with the PhLp treatment reached 0.70, which was greater than any other multi-species combination (Figure 36). The *P. hemitomon* with *A. philoxeroides* (PhAp) and *P. hemitomon* with all edge species (excluding *S. lancifolia,* (Ph edge)) treatments also exhibited a high proportion of total area vegetated, both at approximately 0.63, whereas the *P. hemitomon* with all species (including *S. lancifolia,* (Ph all)) treatment attained moderate vegetative cover at 0.60. The *P. hemitomon* with *H. ranunculoides (*(PhHr) and *P. hemitomon* with *S. lancifolia* (PhSl*)* treatments both attained significantly less vegetative cover (0.36 and 0.38 respectively).

When *P. hemitomon* and each secondary species in two-species combinations were evaluated individually (Figure 37), mixed results were observed with respect to which of the two species contributed more to the proportion of total area vegetated. For the PhLp treatment, a highly significant main effect of time was observed (Wilks' Lambda: $F_{2,5} = 227.81$; $p < 0.0001$) as was a highly significant time by species interactive effect (Wilks' Lambda: $F_{2,5} = 164.64$; $p < 0.0001$). Similar results were observed for the PhAp treatment (Figure 37), including a highly significant main effect of time (Wilks' Lambda: $F_{2,5} = 25.40$; $p = 0.0024$) and a significant time by species interactive effect (Wilks' Lambda: $F_{2,5} = 9.70$; $p = 0.0190$). For both the PhLp and

PhAp treatments, the secondary species attained greater vegetative cover, and therefore contributed more to the proportion of total area vegetated compared to the contribution of *P. hemitomon*. With respect to the PhHr treatment, a significant difference in vegetative cover was observed according to the main effect of time (Wilks' Lambda: $F_{2,5} = 15.20$; p = 0.0075) as was a significant time by species interactive effect (Wilks' Lambda: $F_{2,5} = 9.34$; p = 0.0205).

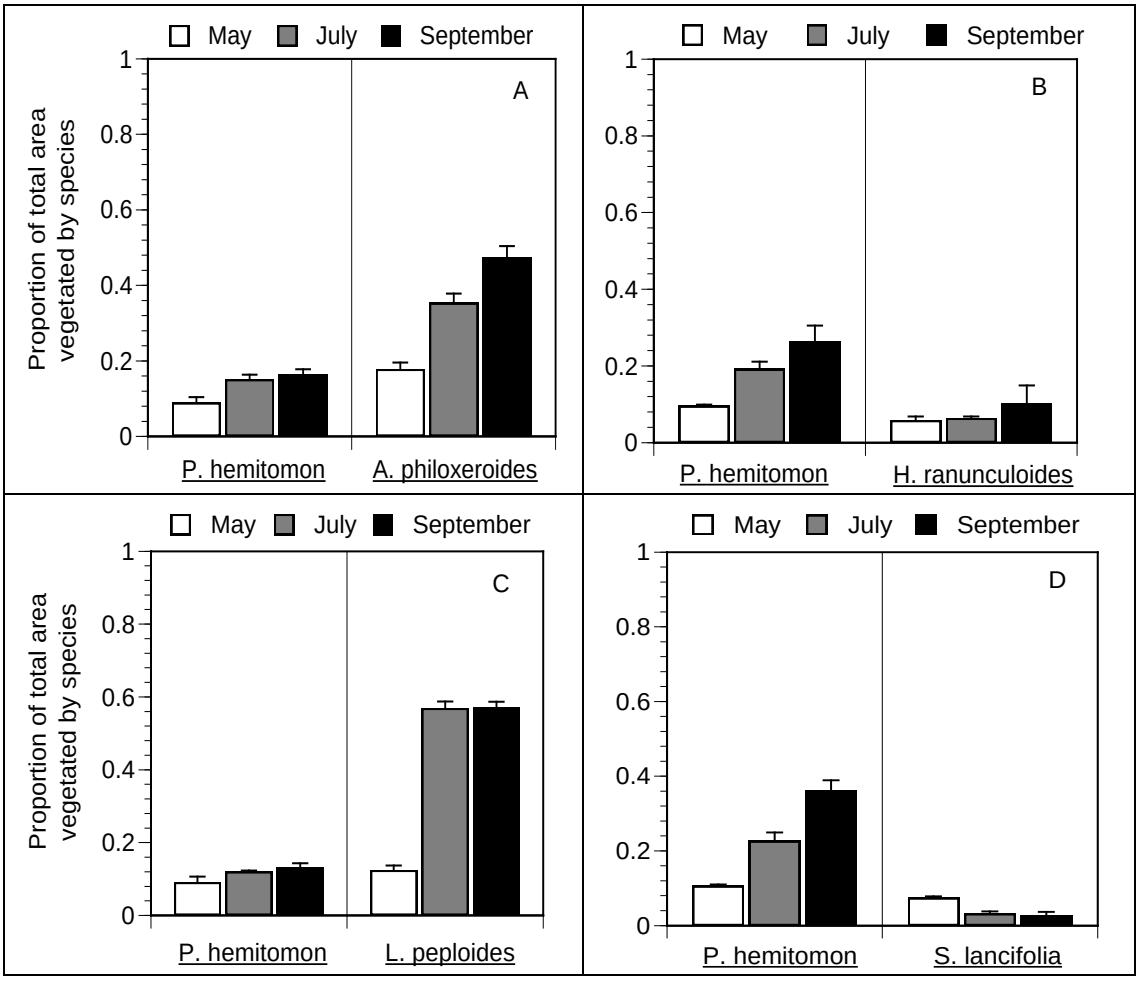

Figure 37. Individual species contribution with respect to the proportion of total area vegetated for each of the two-species treatment combinations measured monthly over a 5-month period. Figure codes are as follows: A = *P. hemitomon* with *A. philoxeroides*; B = *P. hemitomon* with *H. ranunculoides*; C = *P. hemitomon* with *L. peploides*; D = *P. hemitomon* with *S. lancifolia*. Values are means ± SE (n = 4).

As for the PhSl treatment (Figure 37), a significant difference in vegetative cover was also observed in the main effect of time (Wilks' Lambda: $F_{2,5} = 23.01$; p = 0.0030), as well as a significant time by species interactive effect (Wilks' Lambda: $F_{2,5} = 44.05$; p = 0.0007). *P.*

hemitomon, rather than the associated secondary species, exhibited greater vegetative cover in the PhHr and PhSl treatments, which was unlike what was observed with the PhLp and the treatments. Such opposing trends were not expected because it was hypothesized that all secondary species would exhibit greater vegetative cover as a result of growth morphologies that contrasted that of *P. hemitomon*. Rapid lateral expansion of *P. hemitomon* into unvegetated areas was also an initial expectation.

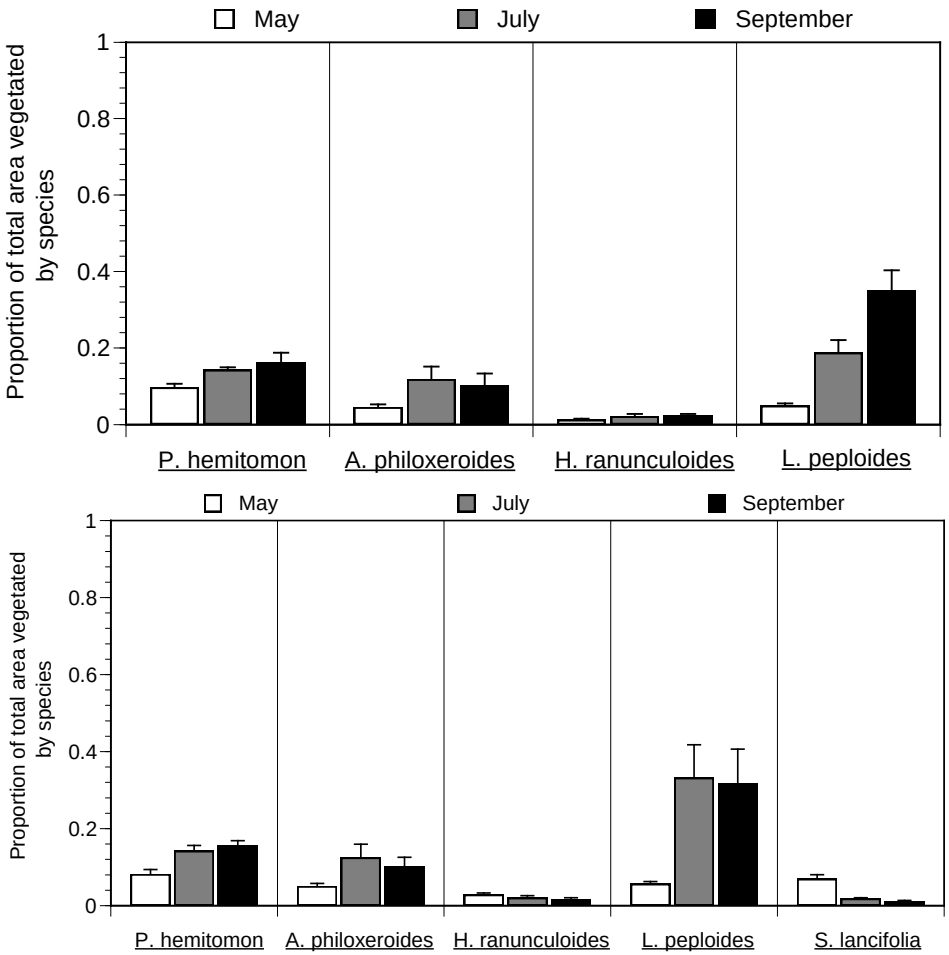

Figure 38. The effect of plant species combination on the proportion of total area vegetated by each species measured monthly over a 5-month period. Top panel represents the edge species treatments that excluded *S. lancifolia* (treatment Ph edge), whereas the bottom panel represents the edge species treatments that included *S. lancifolia* (treatment Ph all). Values are means ± SE (n = 4).

As expected based on results observed for two-species treatments, vegetative cover associated with treatments incorporating more than two species also varied significantly. Considering the *P. hemitomon* with all edge species treatment (Figure 38, top panel), a significant difference in vegetative cover was observed according to the main effect of time (Wilks' Lambda: $F_{2,11}$ = 6.97; p = 0.0111) as well as when the time by species interactive effect was considered (Pillai's

Trace: $F_{8,24}$ = 5.26; p = 0.0007). Similar results were observed with respect to the *P. hemitomon* with all species treatment (Figure 38, bottom panel). A significant difference in vegetative cover was observed with respect to the main effect of time (Wilks' Lambda: $F_{2,14}$ = 5.83; p = 0.0144) and when the time by species interactive effect was considered (Pillai's Trace: $F_{8,30}$ = 2.35; p = 0.0433). In both multi-species treatments previously noted, *L. peploides* was considered the dominant species because it contributed the greatest to the proportion of total area vegetated. However, unlike with the *P. hemitomon* with *A. philoxeroides* two-species treatment in which *A. philoxeroides* exhibited dominance, *P. hemitomon* exhibited secondary dominance in both multi-species treatments.

Root specific gravity (Figure 39) exhibited a highly significant difference across species ($F_{5,24}$ = 191.60; p < 0.0001). *L. peploides* was associated with the lowest root specific gravity (0.12), whereas *A. philoxeroides* was associated with the greatest root specific gravity (0.99).

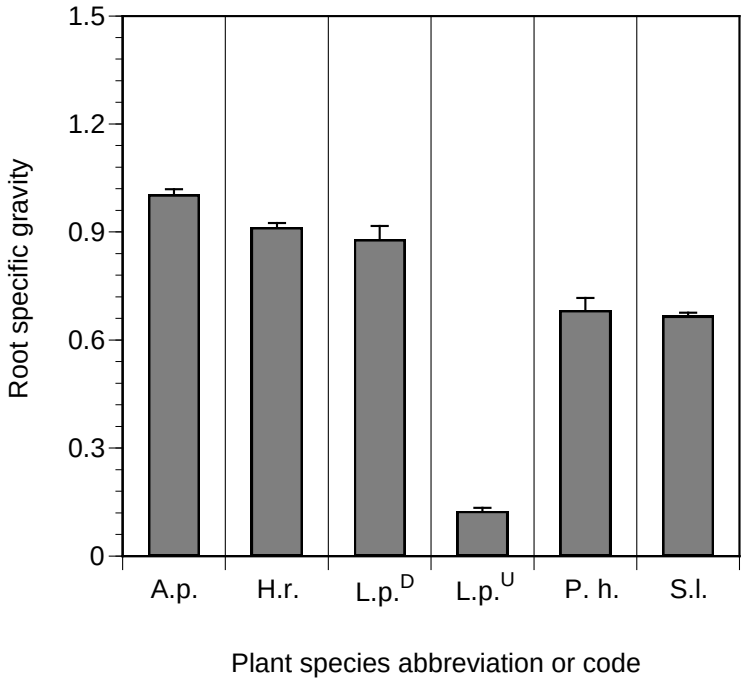

Figure 39. Root specific gravity associated each species included in the multi-species planting approach, all measured on live root tissue sampled from the PD all treatment. Treatment codes are as follows: P.h. = *P. hemitomon*; A.p. = *A. philoxeroides*; H.r. = *H. ranunculoides*; L.p.^{D} *L. peploides* downward-growing root; L.p.^{U} = *L. peploides* upward-growing root; S.l. = *S. lancifolia*. Values are means ± SE (n = 5).

Interestingly, *L. peploides* produces two types of root anatomies:, downward- and upward-growing roots. Unlike their upward-growing counterparts, which were highly buoyant, downward-growing roots were much less so, although still sufficiently buoyant (0.87). *P. hemitomon* and *S. lancifolia* root tissue exhibited similar root specific gravity (0.68 and 0.65 respectively).

Each of the individual root morphological metrics varied widely across species (Table 10). A highly significant difference was observed for total root length ($F_{4,15} = 20.97$; $p < 0.0001$), with *L. peploides* roots exhibiting the greatest total length predominantly because of their herringbone morphology and the sheer number of first-order lateral roots. Roots of *P. hemitomon* have fewer lateral roots and were consequently shorter in total length, although still longer than each of the other species. A highly significant difference was also observed for root diameter ($F_{4,15} = 10.93$; $p = 0.0002$).

Table 10. Individual root diameter (mm), root length (cm), root volume (cm3), and number of root tips for each of the five plant species used to assess multi-species effects on floating marsh vegetative development. All root tissue was sampled from the Ph with all species treatment. Values are means ± SE (n = 4).

Species	Diameter (mm)	Length (cm)
A. philoxeroides	0.18 ± 0.004^{c}	54.7 ± 8.44^{b}
H. ranunculoides	0.39 ± 0.029^{bc}	18.7 ± 0.50^{b}
L. peploides	0.32 ± 0.022^{bc}	535.7 ± 85.4^{a}
P. hemitomon	0.62 ± 0.105^{a}	153.5 ± 61.7^{b}
S. lancifolia	0.54 ± 0.035^{ba}	35.2 ± 2.69^{b}
F – value $_{(df\ 4,15)}$	10.93^{**}	20.97^{**}

Species	Volume (cm^3)	Number of tips
A. philoxeroides	0.01 ± 0.001^{b}	117.7 ± 11.77^{b}
H. ranunculoides	0.02 ± 0.004^{b}	7.75 ± 4.46^{b}
L. peploides	0.61 ± 0.016^{a}	1972.2 ± 871.65^{a}
P. hemitomon	0.34 ± 0.058^{ba}	299.7 ± 147.44^{ba}
S. lancifolia	0.07 ± 0.006^{b}	112.2 ± 4.95^{b}
F – value $_{(df\ 4,15)}$	11.20^{**}	4.39^{*}

[a] Means with same letter in same column are not statistically different ($p < 0.05$) based on Tukey's multiple comparison procedure for all possible pairwise comparisons.
[*] Significant difference ($p < 0.05$); [**] highly significant difference ($p < 0.01$).

P. hemitomon mean root diameter was greater than each of the secondary species. There were also highly significant species differences in root volume across species ($F_{4,15}$ = 11.20; p = 0.0002). The greatest root volume was associated with *L. peploides*. Although less, *P. hemitomon* root volume was still greater than each of the secondary species. Much like root length and diameter, the number of root tips varied significantly across species ($F_{4,15}$ = 4.39; p = 0.0151). *L. peploides* exhibited the greatest number of root tips, again attributable to its herringbone morphology. Importantly, *L. peploides* roots exhibit a greater number of first-order lateral roots, whereas *P. hemitomon* roots branch more extensively beyond the first order division, a trait indicative of fibrous root systems.

P. hemitomon aboveground biomass did not vary significantly with respect to multi-species treatment (Table 11; $F_{6,21}$ = 1.29; p = 0.3037) although it did range from 78.7 g (Ph all treatment) to 111.7 g (Ph treatment). Unlike aboveground biomass, *P. hemitomon* rhizome biomass associated with the multi-species approach (Table 11) exhibited a significant treatment effect ($F_{6,21}$ = 3.19; p = 0.0219), ranging from 55.9 g (PhLp treatment) to 101.9 g (Ph treatment).

Table 11. P. hemitomon dry biomass values (g), partitioned by component, (stem/leaf, rhizome, and root contributions) for each of the multi-species treatments. Peat served as the substrate material and Duralast coconut fiber as the mat or containment material in all treatments. Treatment codes are as follows: Ph = *P. hemitomon* only; PhAp = *P. hemitomon* with *A. philoxeroides*; PhHr = *P. hemitomon* with *H. ranunculoides*; PhLp = *P. hemitomon* with *L. peploides*; PhSl = *P. hemitomon* with *S. lancifolia*; Ph all = *P. hemitomon* with all species; Ph edge = *P. hemitomon* with all species except *S. lancifolia*. Values are means ± SE (n = 4).

Treatment	*P. hemitomon* biomass (g)			*P. hemitomon*
	stem/leaf	rhizome	root	total biomass (g)
Ph	111.7±11.4[a]	101.9±9.0[a]	87.3±17.3[a]	300.9±37.4[a]
PhAp	90.5±15.4 [a]	78.6±16.6[ba]	94.5±16.3[a]	263.8±95.3[a]
PhHr	83.2±7.0[a]	71.5±6.9[ba]	78.1±6.6[a]	232.9±38.7[a]
PhLp	88.3±1.9 [a]	55.9±3.22[ba]	87.5±4.5[a]	231.8±17.2[a]
PhSl	90.4±4.9[a]	92.7±8.6[ba]	97.1±15.6[a]	280.3±48.1[a]
Ph all	78.7±7.2[a]	67.3±5.1[ba]	84.8±5.6[a]	230.96±22.7[a]
Ph edge	88.6±9.1[a]	79.5±2.1[b]	90.8±6.5[a]	259.0±33.6[a]
F – value $_{(df\ 6,21)}$	1.29[NS]	3.19[*]	0.29[NS]	1.27[NS]

[a] Means with the same letter in the same column are not statistically different (p < 0.05) based on Tukey's multiple comparison procedure for all possible pairwise comparisons. [*] Significant difference (p < 0.05); [NS] non-significant difference (p > 0.05).

Similar to that of aboveground biomass, *P. hemitomon* root biomass associated with the multi-species approach (Table 11) did not vary significantly according to treatment ($F_{6,21}$ = 0.29; p = 0.9331) although it did range from 78.1 g (PhHr treatment) to 97.1 g (PhSl treatment). *P. hemitomon* total biomass, a collective measure including stems and leaves, rhizomes, and roots did not exhibit a significant treatment effect across multi-species treatments (Figure 40; $F_{6,21}$ = 1.27; p = 0.3137). *P. hemitomon* total biomass ranged from 231.8 g (PhLp treatment) to 300.9 g (Ph treatment).

As expected based on plant cover data, total mat biomass associated with the multi-species treatments (Table 12), taking into account the individual masses for *P. hemitomon* and each secondary species when present, exhibited a highly significant treatment effect ($F_{6,21}$ = 15.77; p < 0.0001) despite the fact that *P. hemitomon* total biomass did not vary across treatment. With respect to two-species combinations, there was a trend for decreased *P. hemitomon* production when accompanying secondary species performed well. However, as indicated this trend was not significant.

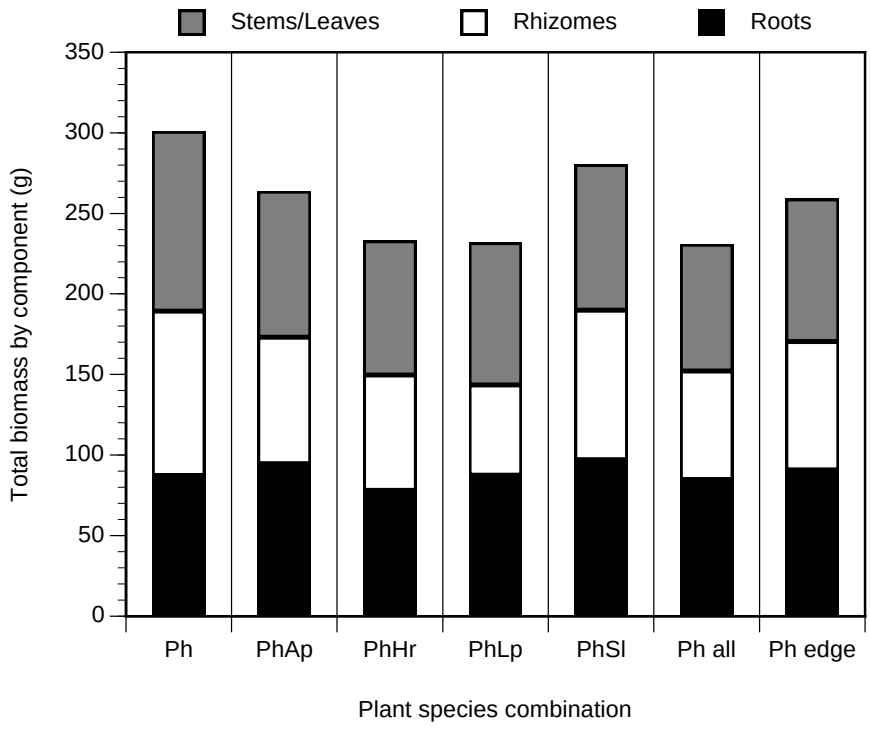

Figure 40. The effect of multi-species combination on *P. hemitomon* total biomass (g) partitioned into individual biomass components (stems/leaves rhizomes, and roots). Treatment codes are as follows: Ph = *P. hemitomon* only; PhAp = *P. hemitomon* with *A. philoxeroides*; PhHr = *P. hemitomon* with *H. ranunculoides*; PhLp = *P. hemitomon* with *L. peploides*; PhSl = *P. hemitomon* with *S. lancifolia*; Ph all = *P. hemitomon* with all species (including *S. lancifolia*); Ph edge = *P. hemitomon* with all edge species (excluding *S. lancifolia*). Values are means ± SE (n = 4).

Table 12. Total dry biomass (g) for all species per multi-species treatment. Columns represent plant tissue dry mass (g), whereas rows represent specific treatment combinations. Column codes are as follows: A.p. = *A. philoxeroides*; H.r. = *H. ranunculoides*; L.p. = *L. peploides*; P.h. = *P. hemitomon*; S.l. = *S. lancifolia*. Row codes are as follows: Ph = *P. hemitomon* only; PhAp = *P. hemitomon* with *A. philoxeroides*; PhHr = *P. hemitomon* with *H. ranunculoides*; PhLp = *P. hemitomon* with *L. peploides*; PhSl = *P. hemitomon* with *S. lancifolia*; Ph all = *P. hemitomon* with all species (including *S. lancifolia*); Ph edge = *P. hemitomon* with all edge species (excluding *S. lancifolia*). Values are means above (SE) (n = 4).

	Plant species					
Treatment	A. p.	H. r.	L. p.	P. h.	S. l.	Totals
Ph	----	----	----	300.99[a] (34.46)	----	313.49[c] (29.29)
PhAp	466.81[a] (61.03)	----	----	263.80[a] (95.37)	----	732.55[b] (180.03)
PhHr	----	15.3[a] (6.63)	----	232.90[a] (38.77)	----	248.20[d] (46.87)
PhLp	----	----	764.3a (78.95)	231.87[a] (17.25)	----	995.72[a] (158.13)
PhSl	----	----	----	280.35[a] (48.13)	55.48[a] (16.88)	338.48[c] (51.44)
Ph all	138.50[b] (24.28)	9.39[a] (3.66)	209.95[b] (82.60)	230.96[a] (22.70)	28.17[a] (3.49)	616.97[b] (222.75)
Ph edge	121.45[b] (36.94)	4.38[a] (1.28)	166.85[b] (41.79)	259.00[a] (33.68)	----	551.90[b] (117.79)
F – value $_{(df\ 6,21)}$				1.27^{NS}		15.77^{**}
F – value $_{(df\ 2,11)}$	19.30^{**}	1.54^{NS}	22.50^{**}			
F – value $_{(df\ 1,7)}$					2.48^{NS}	

[a] Means with the same letter in the same column are not statistically different ($p < 0.05$) based on Tukey's multiple comparison procedure for all possible pairwise comparisons. ** Highly significant difference ($p < 0.01$); ^{NS} non-significant difference ($p > 0.05$).

P. hemitomon total rhizome length (Table 13), measured using freshly-harvested rhizome material, varied significantly according to multi-species combination technique ($F_{11,36} = 21.66$; $p < 0.0001$).

Table 13. P. hemitomon total rhizome length (cm) and estimated root volume (cm3) with respect to each multi-species combination. Treatment codes are as follows: Ph = *P. hemitomon* only; PhAp = *P. hemitomon* with *A. philoxeroides*; PhHr = *P. hemitomon* with *H. ranunculoides*; PhLp = *P. hemitomon* with *L. peploides*; PhSl = *P. hemitomon* with *S. lancifolia*; Ph all = *P. hemitomon* with all species (including *S. lancifolia*); Ph edge = *P. hemitomon* with all species (excluding *S. lancifolia*). Values are means ± SE (n = 4).

Treatment	*P. hemitomon* total rhizome length (cm)	*P. hemitomon* estimated root volume (cm^3)
Ph	45.5 ± 4.07^{bc}	504.5 ± 100.29^{ba}
PhAp	35.4 ± 5.83^{a}	546.05 ± 94.39^{a}
PhHr	32.5 ± 3.27^{a}	451.1 ± 38.67^{ba}
PhLp	28.9 ± 2.60^{a}	505.7 ± 26.36^{ba}
PhSl	39.8 ± 3.92^{bcd}	561.1 ± 90.3^{a}
Ph all	28.4 ± 2.00^{e}	490.1 ± 32.36^{ba}
Ph edge	34.8 ± 1.16^{ed}	524.5 ± 37.61^{a}
F – value $_{(df\ 11,36)}$	21.66^{**}	9.29^{**}

[a] Means with the same letter in the same column are not statistically different ($p < 0.05$) based on Tukey's multiple comparison procedure for all possible pairwise comparisons. ** Highly significant difference ($p < 0.01$).

The role of species diversity and multi-species planting approaches on ecosystem-level processes, particularly their influence on the restoration of ecosystem function is well demonstrated in the ecological literature. In addition to increases in accumulated biomass, species diversity has been linked to increased productivity (Naeem et al. 1994), enhanced nutrient retention (Ewel et al. 1991), ecosystem resilience (Tilman and Downing 1994), reliability (Johnson et al. 1996; Naeem and Li 1997), and decreased invasibility by other species (Tilman et al. 1997; Symstad 2000). Evidence also exists suggesting that particular chemical and biological attributes of wetland soil and vegetation can be modified or augmented through multi-species planting approaches (Zedler et al. 2001; Zedler 2005). In general, an overarching theme associated with multi-species approaches is that they should be focused on identifying species or combinations of species that have a disproportionately positive effect on achieving particular objectives. The proportion of total area vegetated provided an initial clue into which multi-species grouping and plant establishment technique were most beneficial from the perspective of thick-mat floating marsh creation. Considering the primary objective of this experiment, at least in regards to the effect of multiple species on overall vegetative development and mat structural integrity, it would seem that treatments with a greater number species would incur an advantage over treatments with fewer species, particularly if the species under consideration minimize direct competition for resources by occupying different ecological niches. Interestingly, treatments with a greater number of species were not necessarily associated with greater vegetative cover, and by the end of the experiment it was clear that specific combinations were far more robust, and therefore more suitable for field testing than others.

The effects of inter-specific competition and competitive exclusion on plant growth and performance are well documented (Connell and Slatyer 1977; Grime 1979; Tilman 1982), although it was unclear at the outset of this experiment whether or not any particular species would possess a competitive advantage. Over the course of the experiment, and certainly by its completion, the trend for greater *P. hemitomon* total biomass when grown independently as compared to when grown in combination with another species is suggestive of such interactions, keeping in mind that this trend was not significant. Although it appeared that individual plant morphologies differed in such a way as to minimize competition for light, less is known regarding the mineral nutrient requirements of each of the species and whether or not the nutrient regime as applied was sufficient to satisfy species-specific requirements. Nevertheless, competitive interactions were present because differences in total plant biomass for several species were observed across treatments in which the same species were present. Such differences could be explained by variability in specific nutrient requirements, or by differing degrees of competition-induced nutrient limitation. Minimum nutrient requirements vary by species (Chapin 1980) and such requirements may not have been satisfied in those treatments in which secondary species did poorly. Alternatively, in those treatments where certain secondary species performed well, such differences could be explained by non-limiting nutrient availability. While it is likely that each of these effects had some influence on the findings presented here, it was concluded that stressors associated with transplanting and inundated hydrologic conditions were also influential, especially for the three secondary species that performed poorly. Although it is plausible that the condition of poorly-performing species could have improved over time, it was surmised that five months of growth was sufficient considering the creation and restoration context of this research. It seemed clear that the fragility and lack of transplanting resilience of *H. ranunculoides* was a major obstacle affecting its survivorship, whereas *A. philoxeroides*, despite its moderately good performance, may ultimately prefer less flooded, more mesic conditions. This seemed apparent despite the fact that *A. philoxeroides* is typically associated with aquatic settings. *A. philoxeroides* may perform better under conditions in which the main rooting body is not continuously inundated or submersed as it was here. *S. lancifolia* was expected to perform well in the created mats because it is tolerant of prolonged inundation and flooding (Chabreck 1972; Stutzenbaker 1999). Despite these assumptions, *S. lancifolia* performed as poorly as *H. ranunculoides*, losing a substantial amount of aboveground biomass over the course of the experiment. Interestingly though, upon harvest of those mats in which *S. lancifolia* was present, a considerable amount of new *S. lancifolia* biomass was observed emerging from the underside of each mat, all associated with the main rooting bodies that were initially planted. Nevertheless, *S. lancifolia* total biomass was extremely low at harvest, particularly for a species that at times exhibits co-dominance in naturally-formed thick-mat floating marsh, conditions that were closely mimicked. Considering that all treatments were exposed to full-light conditions, and that each species exhibited a different growth form, it seems reasonable to infer that incidental shading was not a major factor in any particular species performing poorly.

After one month of growth it became clear that *L. peploides* found conditions inherent in the created mats highly favorable. Of all the species included in this experiment, *L. peploides* seemed to be particularly well-suited to semi-immersed conditions. Cuttings of *L. peploides* exhibited the most resistance to transplanting stress, although *P. hemitomon* is also resistant to transplanting stress even in the absence of formal propagation. *L. peploides* grew rapidly and

attained extensive vegetative cover after only three months of growth, and had it not been for a moderate insect-induced defoliation event between sampling months three and four, it is likely that total biomass would have been considerably greater at harvest than what was documented. It is also likely that *L. peploides* would have attained greater biomass had it not been for size limitations associated with the experimental vessels. *L. peploides* exhibited rapid and dense lateral growth, and unlike each of the other secondary species, it extensively colonized interior portions of created mats in which it was planted. Such growth, in conjunction with that of *P. hemitomon,* contributed considerably to the overall structural integrity of created mats when they were both present. These effects were most apparent at harvest when each root and rhizome had to be separated from the coconut fiber material. This notion is further supported by the fact that *L. peploides* and *P. hemitomon* exhibit different growth forms with respect to both above- and belowground components. Like most grasses, *P. hemitomon* grows vertically (Godfrey and Wooten 1979a), whereas *L. peploides* is a low-stature herbaceous dicot that grows in a pronounced lateral fashion on the water's surface (Godfrey and Wooten 1979b). The leaves of *L. peploides* are oblate and occur in small clusters emerging from each stem node, whereas those of *P. hemitomon* are slender and erect. The propensity for rapid lateral growth by *L. peploides*, and the tendency for each tiller to vegetatively subdivide into multiple tillers makes *L. peploides* particularly effective for use in floating marsh creation.

The more species-diverse treatments were not necessarily associated with the greatest proportion of total area vegetated. However, all two-species treatments exhibited greater cover than that exhibited by the *P. hemitomon* only treatment. In these treatments species such as *L. peploides* and *A. philoxeroides*, but predominantly *L. peploides*, tended to exhibit dominance. The *P. hemitomon* with all species (including *S. lancifolia*) and the *P. hemitomon* with all edge species (excluding *S. lancifolia*) treatments, despite including a greater number of species (5 and 4 respectively), were associated with less vegetative cover than either the *P. hemitomon* with *L. peploides* or the *P. hemitomon* with *A. philoxeroides* treatments. The dominance of *L. peploides* was further substantiated by the fact that it independently accounted for the greatest proportion of the total cover in the *P. hemitomon* with all species (including *S. lancifolia*) and the *P. hemitomon* with all edge species (excluding *S. lancifolia*) treatments.

When two-species combinations were considered, *P. hemitomon* total cover varied depending on what secondary species it was coupled with. For example, *P. hemitomon* total cover was significantly less when coupled with *L. peploides* or *A. philoxeroides*, the two best performing laterally-growing specialists. Alternatively, when coupled with either *H. ranunculoides* or *S. lancifolia*, *P. hemitomon* total cover was significantly greater than the secondary species. As would be expected, *P. hemitomon* total cover tended to decrease with concordant increases in the secondary species with which it was coupled.

The notion of including additional species in a protocol for creating thick-mat floating marsh has many potential benefits that extend beyond simply increasing species richness. In particular, additional species such as *L. peploides* possess qualities that may enhance mat lateral expansion. *P. hemitomon* rhizomes almost exclusively occur belowground, or in this case within the created mat, whereas those of *L. peploides* are almost exclusively aboveground. Identifying such morphological differences was of interest because of the potential benefits associated with augmenting or enhancing fusion or coalescence among adjacent created mats. Laterally-

spreading tillers of *L. peploides* tillers, along with specific root system attributes, such as highly buoyant upward-growing roots, further bolster the potential of *L. peploides* to positively contribute to the development of vegetatively integrated and structurally sound thick-mat floating marsh.

As noted, root morphology and root specific gravity are two metrics that varied significantly across species. Species with root systems that bolster mat structural integrity are most desirable from the perspective of marsh creation. Furthermore, root tissue that is sufficiently buoyant is not simply desirable but imperative so as to not compromise or negatively affect marsh buoyancy. In addition to sufficiently satisfying all other requirements, *L. peploides* is the only secondary species that sufficiently met these requirements as well. Roots of *A. philoxeroides*, *H. ranunculoides*, and *S. lancifolia* all appeared ineffective at contributing to the overall strength of the created mat because of root morphological attributes. Each of these species, but particularly *H. ranunculoides* and *A. philoxeroides*, produced roots that were either delicate and feathery, or roots that essentially lacked the capacity for sufficient lateral growth. *L. peploides* on the other hand rooted extensively through created mats, produced roots with many first-order branches, and exhibited sufficiently buoyant downward-growing roots. Upward-growing roots on the other hand were extremely buoyant as evidenced by their extremely low specific gravity. The foam-like structures that envelop upward-growing *L. peploides* roots may provide much needed support for laterally expanding tillers (Ellmore 1981).

Experiment-5: Evaluation of P. hemitomon seed production and germination potential.
A significant effect of structural treatment effect on *P. hemitomon* flowering was detected in which structures of PVC and no fence had greater inflorescences per m^2 than bamboo with fence and PVC with fence when planted with stems (Figure 41; Contrast F= 5.745; $p<0.018$). No other significant effects or interactions were detected in terms of inflorescences per m^2.

In terms of flowering morphology, site one had significantly greater florets per inflorescence than sites two and four (Figure 41; Contrast F= 68.729; $p<0.001$). The overall average number of florets per inflorescence was 88.2. A total of 5,730 florets were inspected for seeds. Interestingly, some of the florets did contain seeds, although the seed production rates were extremely low. Of the seeds that were identified, less than one third of them appeared to be mature and potentially viable. The average number of total seeds produced per floret was 0.00314 (or 0.314%). Of these, the number of potentially viable seeds produced per floret was 0.00087 (or 0.087%).

Despite a fairly intensive flowering effort at the floating marsh creation demonstration site at Mandalay NWR, the actual seed production rates were very low, with less than one-tenth of 1% of all florets producing seeds that appeared to be mature and potentially viable. Even if all seeds were considered, including seeds that were clearly non-viable, the percentage is still less than 1%. This is in agreement with what is generally known from observations from other states (Vogl 1973; Hatch et al. 1999; Pfaff and Maura 2000) and anecdotally has been attributed to the common name of this species being ―maidencane" since it produces so few viable seeds.

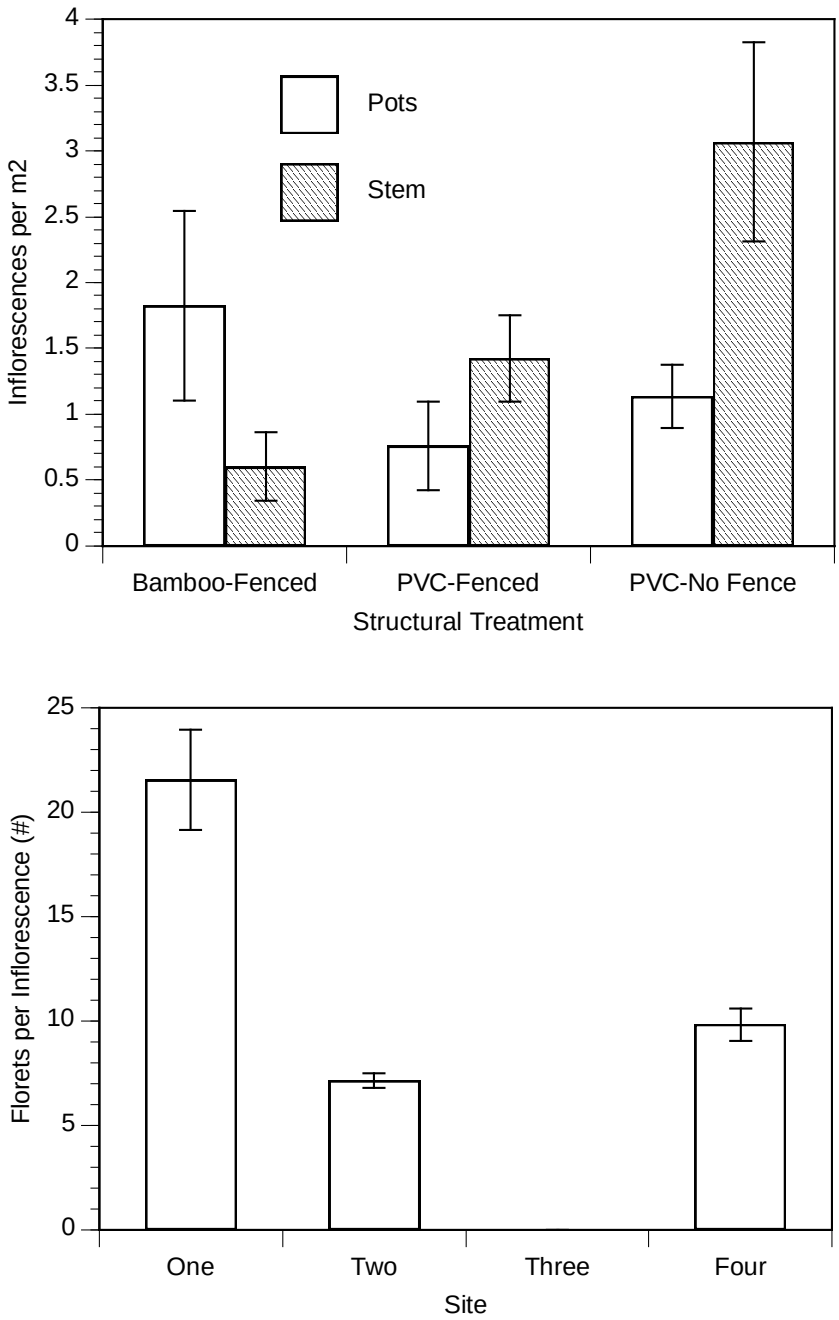

Figure 41. Number of *P. hemitomon* inflorescences (flowering stems) per m^2 by structural treatment and type of planting unit (top panel) and number of florets per inflorescence by site (bottom panel) at the Mandalay NWR floating marsh creation demonstration field-deployment site. Values are means ± SE.

The limited seed production research on *P. hemitomon* does indicate that there can be substantial interannual variation in sexual reproductive effort (Loveless 1959; Vogl 1973), which is similar to what was observed during the span of this project during which only one significant flowering year (2007) was recorded. Environmental stress or the relief from stressful conditions has been reported to induce a flowering response in several plant species, including citrus trees (Southwick and Davenport 1986) and wild mustard (Stanton et al. 2000). The apparent induction of flowering by *P. hemitomon* in wet years following a series of drought years, as reported by Loveless (1959) and Kirkman and Sharitz (1993), may represent such a phenomenon. The role of burning is less clear since Vogl (1973) observed flowering in both burned and control sites post burning. Although speculative, in this study the significant increase in number of flowering stems per unit area in the PVC structures with no fencing may be related to a greater intensity of herbivore (nutria) grazing on these structures causing the plants to shift their patterns of energy allocation away from vegetative growth (asexual reproduction) to sexual reproduction.

Regardless of the mechanisms that may trigger greater sexual reproductive episodes in *P. hemitomon*, it appears that the numbers of viable seeds produced will still be low. The unpredictable interannual variation in sexual reproductive effort combined with low seed production rates, even when a greater number of inflorescences are produced, make the use of seeds as an alternative source of plant material of *P. hemitomon* in thick-mat floating marsh creation/restoration projects an untenable option at this time.

Field Deployment

Structural Integrity and Buoyancy

After the PVC structures were deployed in early June 2006, a few (<1%) lost buoyancy because a PVC buoyancy tubes was not watertight. This was most likely caused by incomplete gluing of the PVC caps or hairline fractures in the PVC from transport. Each of these structures was repaired by adding an additional PVC tube to the structure. These repairs restored buoyancy of the affected structures to the same level as the buoyancy of structures that did not require repair. These repairs are considered quality control repairs as part of the construction period. None of the monitored structures required repairs in post construction. In October 2006, two of the monitored unfenced PVC structures, developed leakage in one of their buoyancy tubes. However, even with the leaking buoyancy tubes, the majority of the two structures remained floating at the surface. These structures were repaired by attaching a new PVC buoyancy tube to the failing tube to fully restore their buoyancy. These repairs were performed to give all structures a complete first growing season with full buoyancy. No structural failure was observed during the first growing season and all structures remained in buoyancy class 1 (majority of the structure floating on the water surface).

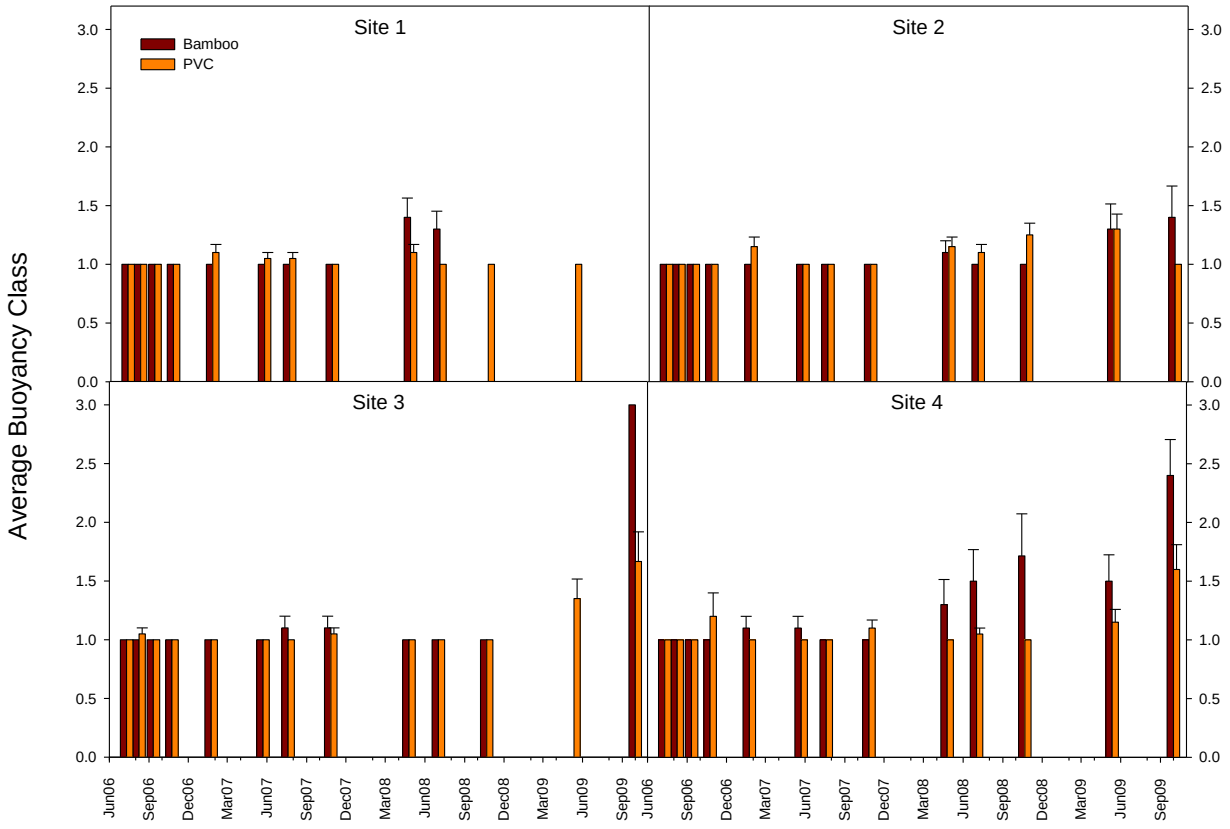

Figure 42. Average buoyancy class of PVC and bamboo structures during the monitoring period. Buoyancy classes are as follows 1= floating, 2 = submerged floating, 3 = sunken.

Four of the 200 PVC structures (2%) were categorized as class 2 (submerged floating, 0 -15 cm below the water surface) during the second growing season (2007). All of the bamboo structures remained fully buoyant. Corrosion of the wire mats was first observed in the PVC structures at site 3 in July of 2007, but this corrosion did not affect the stability of the structures (Figure 42).

On April 25, 2008 it was observed that corrosion of the wire mats had occurred at all the sites and this negatively affected the protection from grazing in most of the fenced structures. In addition, a boat must have hit the outer bamboo structures at site 4, which resulted in the sinking of one structure (buoyancy class 3), and the submerged floating of another (buoyancy class 2). By July 7, 2008 the submerged-floating bamboo structure had also sunk and one additional structure was classified as submerged floating. On October 22, 2008 after Hurricanes Gustav and Ike, there were three of the bamboo structures that could not located, adjacent to were the initial boat hit took place, and two other bamboo structures sank and one bamboo structure was floating submerged.

On April 25, 2008 there were a few PVC (2 at site 1, and 3 at site 2) and bamboo structures (4 at site 1 and 1 at site 2) classified as submerged floating. Three of the PVC structures were floating by July, but one new PVC structure at site 4 was added to the list of submerged floating structures. Only two of the bamboo structures were floating in July. Three submerged-floating bamboo structures remained at site 1. After Hurricanes Gustav and Ike it was difficult to identify the bamboo structures at site 1, because strings keeping the structures in place had broken and the structures had been rearranged. After the hurricanes, the 10 monitored PVC structures planted with stems at site 1 disappeared. Furthermore, five of the PVC structures at site 2 were classified as submerged floating.

Overall, the structures performed well through the 2008 hurricane season with 81% of the monitored structures remaining a float and structurally intact. Corrosion and the lack of vegetation development in the bamboo structures at site 3 lead to the structural collapse of most of these structures by September 2009.

Nutrient Availability

Ammonium in the surface water in July 2006 ranged from 0.31 to 2.88 mg/l, with the highest average ammonium concentrations occurring at sites 1 and 4 and the lowest at site 3 (Table 14). Ammonium concentrations in the surface water declined as the growing season progressed. Nitrate-nitrite in the surface water ranged from 0.16 to 5.80 mg/l, with the highest average nitrate-nitrate concentrations occurring at site 1 and lowest at site 4 (Table 14). Nitrate-nitrite concentrations also declined as the growing season progressed. Phosphate in the surface water ranged from 0.10 to 0.86 mg/l, with the highest average phosphate concentrations occurring at site 1 and lowest at site 4 (Table 14). September nutrient concentrations were very similar for the average fall surface water concentrations in the Penchant basin (Sasser et al. 2005). The nutrient concentrations in July were sufficient for *P. hemitomon* growth and no fertilization of the structures was necessary.

Table 14. Average nutrient concentrations (mg/l ± 1 standard error) recorded at the 4 sites.

Month	Site	Ammonium	Nitrate-Nitrite	Phosphate
July	1	1.54 ± 0.44	4.34 ± 1.39	0.77 ± 0.10
	2	1.06 ± 0.04	1.19 ± 0.10	0.71 ± 0.06
	3	0.39 ± 0.08	0.68 ± 0.25	0.41 ± 0.04
	4	1.54 ± 0.67	0.32 ± 0.12	0.34 ± 0.12
	All	1.13 ± 0.22	1.63 ± 0.57	0.56 ± 0.07
September	1	0.31 ± 0.05	0.23 ± 0.09	1.07 ± 0.01
	2	0.67 ± 0.22	0.21 ± 0.08	0.95 ± 0.15
	3	0.41 ± 0.08	0.23 ± 0.05	0.62 ± 0.14
	4	1.54 ± 1.10	0.43 ± 0.09	0.71 ± 0.22
	All	0.73 ± 0.28	0.27 ± 0.04	0.84 ± 0.08
October	1	0.24 ± 0.23	0.21 ± 0.11	0.60 ± 0.30
	2	0.02 ± 0.00	0.08 ± 0.02	0.80 ± 0.27
	3	0.29 ± 0.08	0.32 ± 0.04	0.51 ± 0.02
	4	0.08 ± 0.01	0.14 ± 0.00	0.32 ± 0.11
	All	0.17 ± 0.07	0.20 ± 0.04	0.54 ± 0.10

September 2006

June 2006

May 2007

October 2007

May 2009

July 2008

Illustration 20. The progression at site 1 is shown. Note the relatively quick expansion of P. hemitomon. P. hemitomon occupied the space between adjacent structures and a mat is starting to form in the triangle formed by the structures in October 2007.

June 2006

September 2006

May 2007

October 2007

July 2008

May 2009

Illustration 21. The progression at site 2 is shown. Note the relatively quick expansion of P. hemitomon. P. hemitomon occupied the space between adjacent structures and a mat is starting to form in the triangle formed by the structures in October 2007.

June 2006

September 2006

May 2007

October 2007

July 2008

May 2009

Illustration 22. The progression at site 3 is shown. Expansion of P. hemitomon has been fairly slow at this site. However, a large sedge mat has developed around the bamboo structures.

June 2006

September 2006

May 2007

October 2007

July 2008

May 2009

Illustration 23. The progression at site 4 is shown. P. hemitomon expansion at this site has been intermediate. Notice the low vegetative cover in the external compared to internal (not monitored) structures.

Vegetation Cover

Site 1 was the site where the structures were first deployed. This is reflected in the relatively high *P. hemitomon* cover for PVC structures planted with pots in July 2006 (Figure 43). However by the end of the first growing season, all structure types--except the bamboo structures planted with stems—had *P. hemitomon* cover greater than 80%. In the first winter, nutria grazed the aboveground vegetation of unfenced structures. This resulted in a slight reduction in the *P. hemitomon* cover at the start of the second growing season (May 2007). The unfenced structures recovered during the summer, but nutria activity was once again reducing *P. hemitomon* at the end of October 2007. Nutria exclusion failed in the fenced structures over the winter, which resulted in all structures at site 1 having less *P. hemitomon* cover in April 2008. The bamboo structures planted with stems show the effect of late spring deployment. These structures started with the lowest *P. hemitomon* cover in July 2006 and although *P. hemitomon* cover increased during the second growing season, these structures only reached a *P. hemitomon* cover of 60% in October 2007. These structures were also heavily grazed. Other species such as *Bidens laevis, Ludwigia leptocarpa*, and *Limnobium spongia* invaded the vacant space on the structures with reduced *P. hemitomon* cover, so that the structures were almost fully covered with vegetation. The 2008 hurricane season had its largest impact at this site and resulted in the disappearance of the monitored PVC structures planted with stems. In addition, we could not determine which structures were the monitored bamboo-structures, because they were moved out of place.

Site 2 is where the structures were deployed second (Figure 44). The trends in vegetation cover at this site are essentially the same as for site 1. One exception being that the unfenced structures at this site had not been grazed at the end of the second growing season (October 2007). And the other exception being that the structures at this site showed no damage from the 2008 hurricane season.

Site 3 received structures last, which is reflected in the low initial cover in the PVC structures planted with stems (Figure 45). The unfenced structures at this site did not recover as much from the grazing during the winter and the *P. hemitomon* cover at the end of the second growing season was lower than at the end of the first season. The bamboo structures at this site had a very good second growing season and were close to 100% covered with *P. hemitomon* in October 2007. However, *P. hemitomon* cover decreased over the 2008 growing season.

The PVC structures at site 4 showed different trends in the second growing season than all the other sites (Figure 46). Cover of *P. hemitom*on actually declined as the growing season progressed. In October 2007, it was noticed that the water hyacinths in and around the structures were sprayed with herbicides. This especially affected the PVC structures selected for monitoring (Those on the outside of the site that are more easily accessed). The PVC structures that make up the bulk of this site seemed more similar in cover to the other sites. The bamboo structures were less affected, probably because fewer water hyacinths were close to these structures. However the decline of *P. hemitomon* cover continued, especially in the unfenced PVC structures. The bamboo structures planted with stems were negatively affected apparently by a boat that hit these structures in early 2008, which affected their buoyancy.

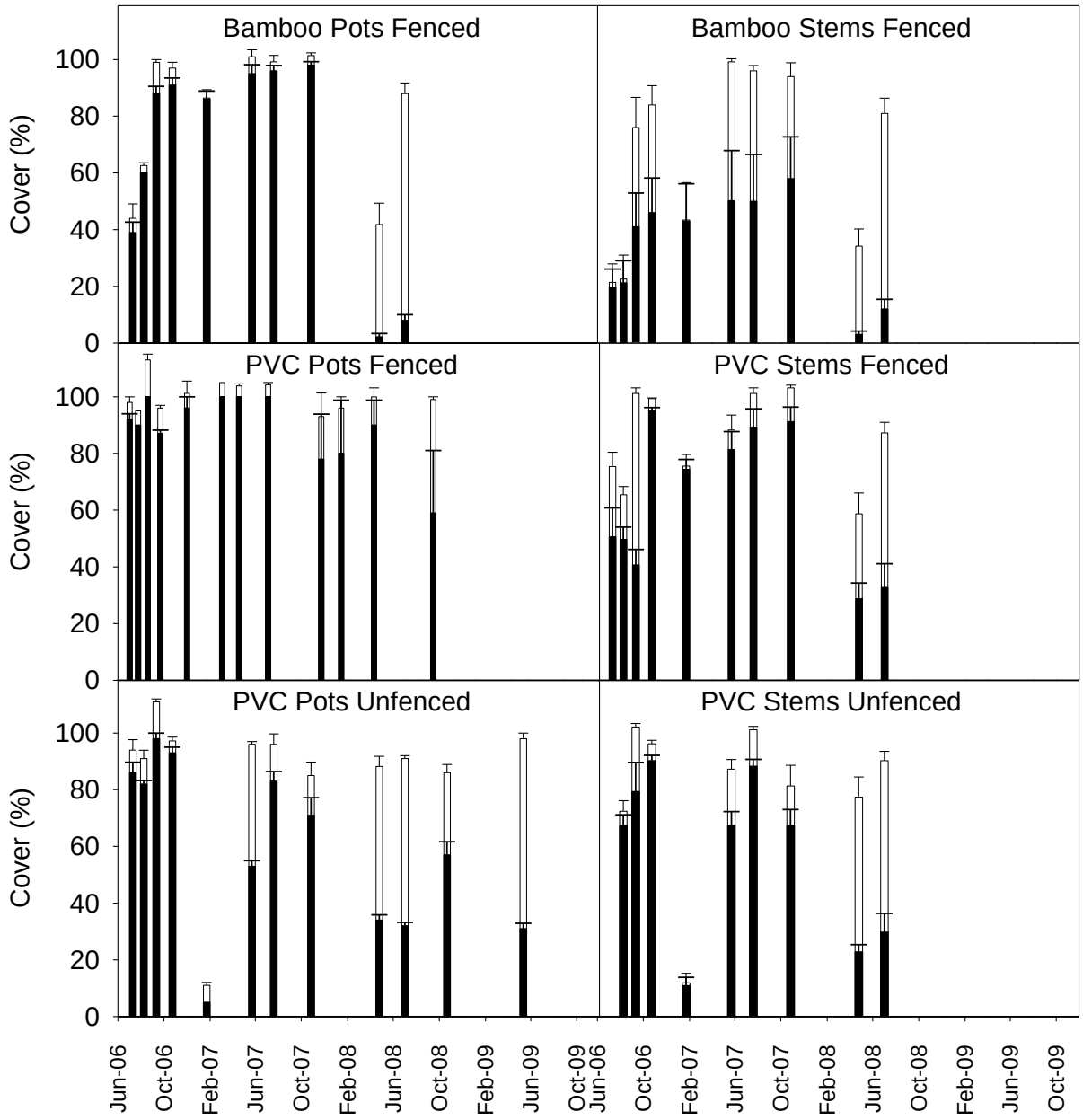

Figure 43. Trends in cover for site 1 by treatment. Closed bars show *P. hemitomon*, while open bars show the total cover. Error bars show one standard error.

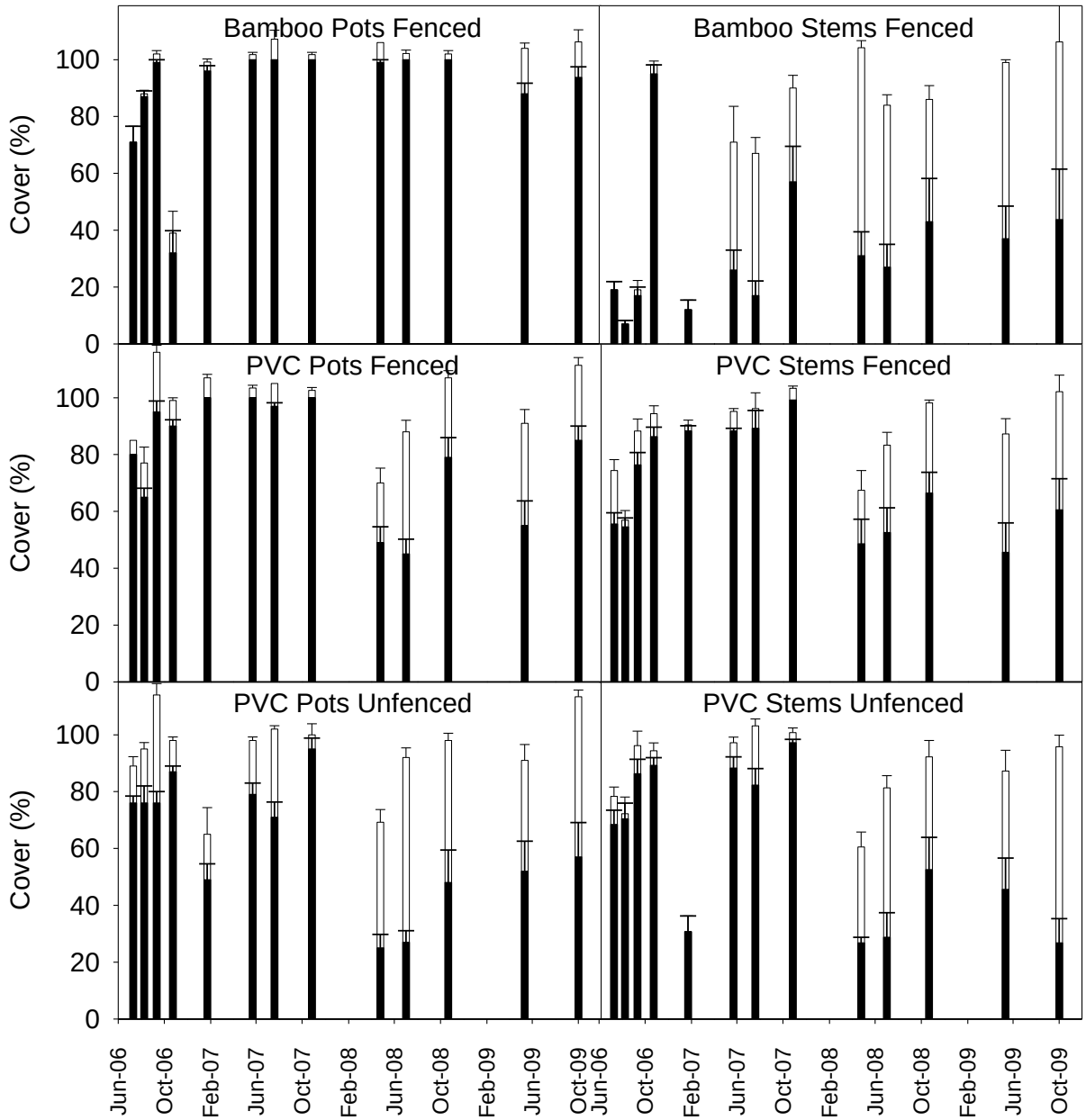

Figure 44. Trends in cover for site 2 by treatment. Closed bars show *P. hemitomon*, while open bars show the total cover. Error bars show one standard error.

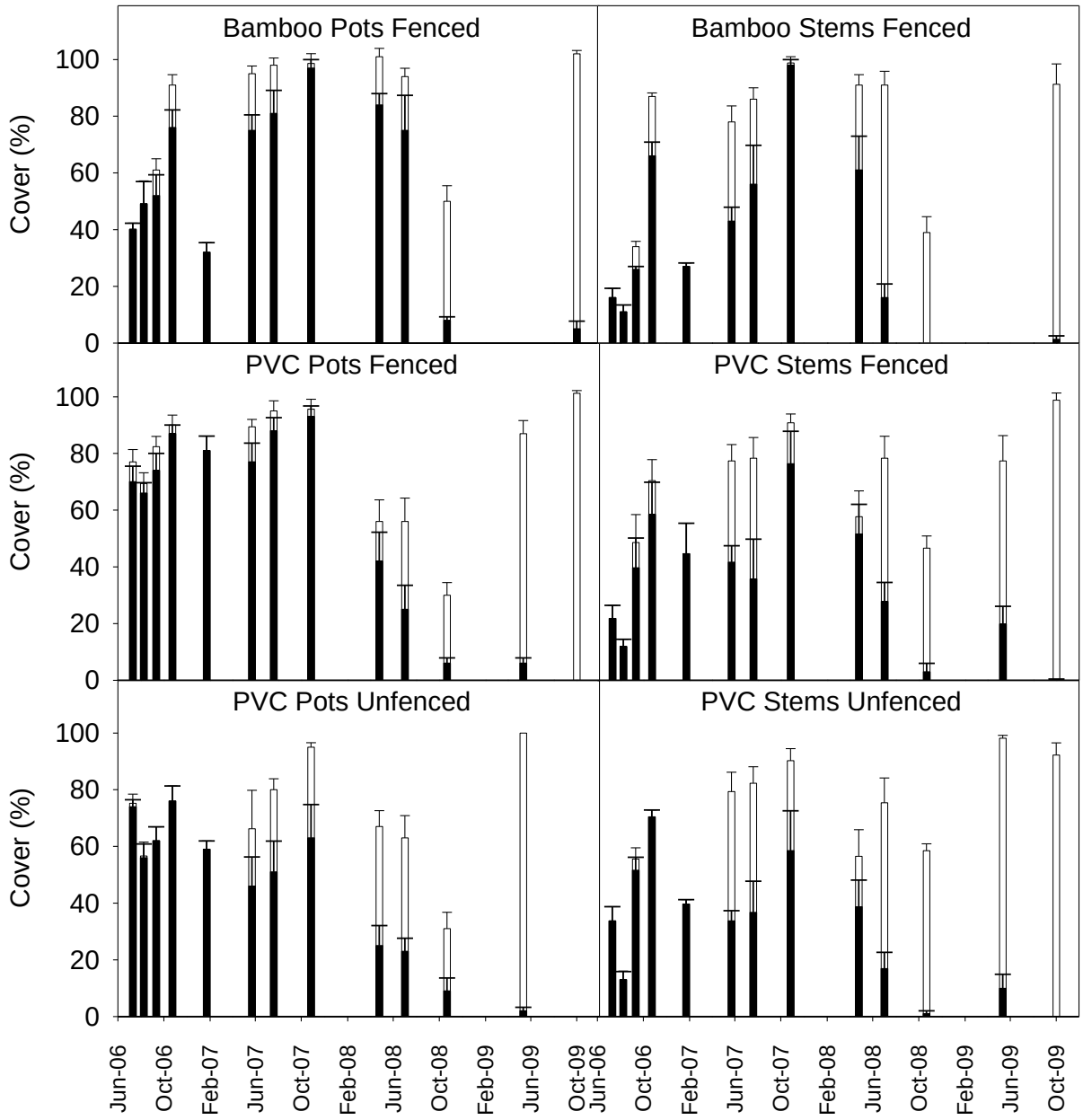

Figure 45. Trends in cover for site 3 by treatment. Closed bars show *P. hemitomon*, while open bars show the total cover. Error bars show one standard error.

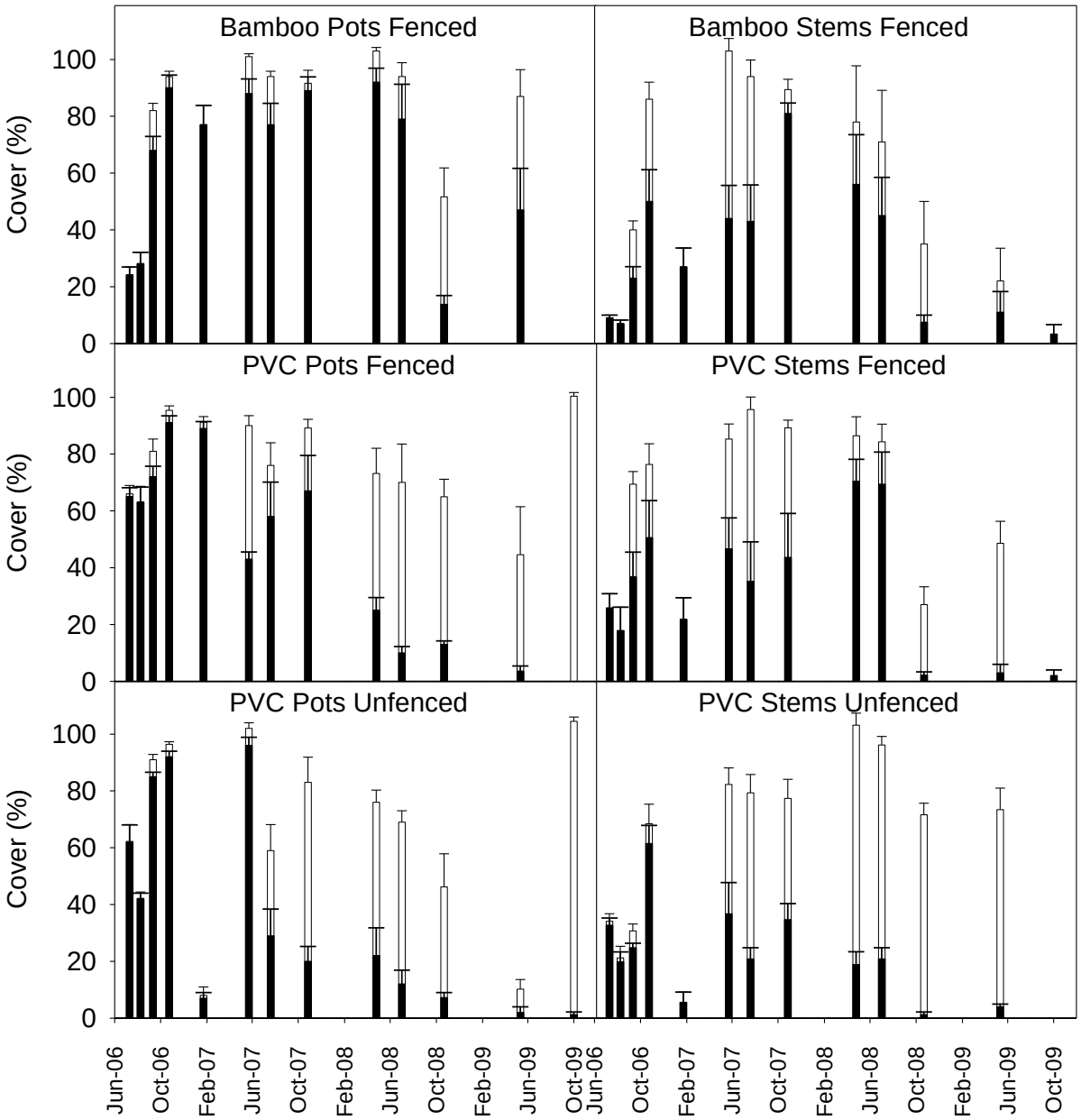

Figure 46. Trends in cover for site 4 by treatment. Closed bars show *P. hemitomon*, while open bars show the total cover. Error bars show one standard error.

Overall, *P. hemitomon* cover decreased in the third year after deployment (Figure 47). This is likely due to the rusting of the chicken-wire mats and the bottom of the fences, which lead to increased grazing by nutria. However, total cover in the structures remained high in 2008 with an average of 85% cover on July 2, 2008. The decrease in cover in October 2008, is probably related to a salinity pulse associated with Hurricane Gustav, which resulted in early senescence of some species, including *P. hemitomon*.

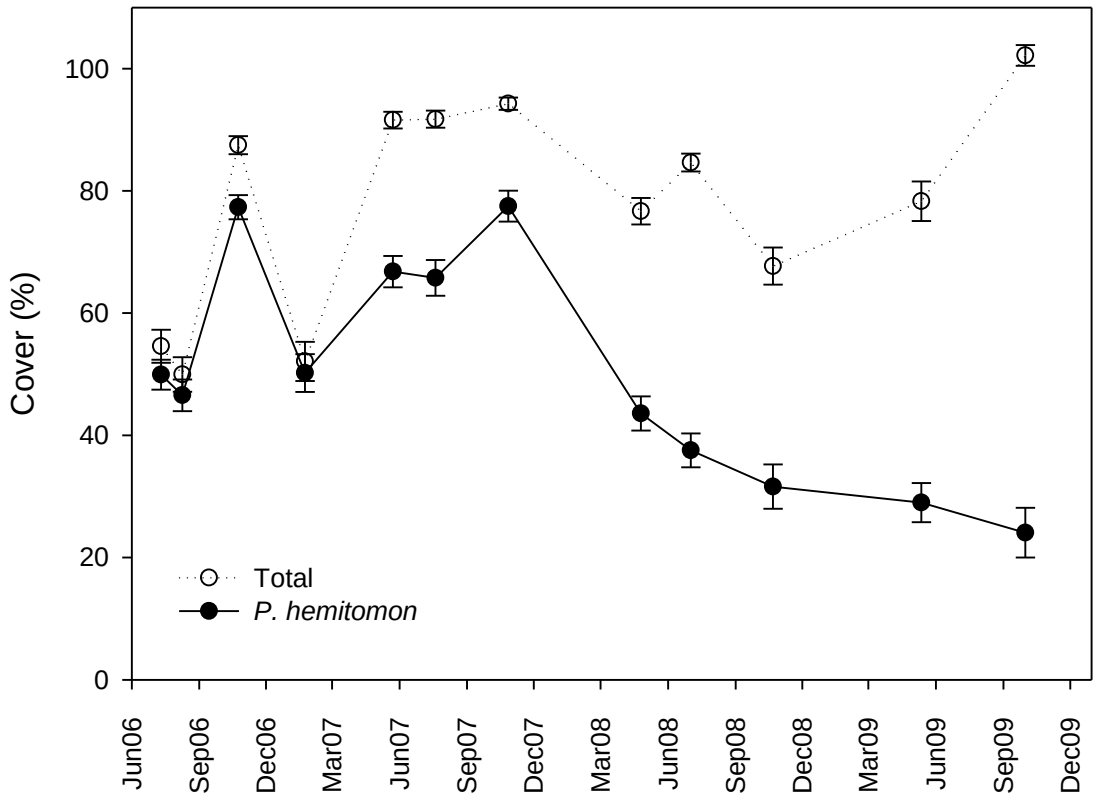

Figure 47. Trends in cover for all monitored structures. Error bars show one standard error.

Panicum hemitomon spread

P. hemitomon started spreading outside the structures through rhizome growth when its cover reached approximately 60%. At the end of the first growing season the average *P. hemitomon* spread from the structures was 10 cm (Figure 48). Early spreading from unfenced structures was mainly due to aerial stems spreading outside the structure. Very few of these stems survived. Structures that obtained higher *P. hemitomon* cover earlier in the growing season spread further (PVC structures planted with pots average spread 13.5 cm in October 2006), than those who obtained cover later in the growing season. Spread significantly increased in the second growing

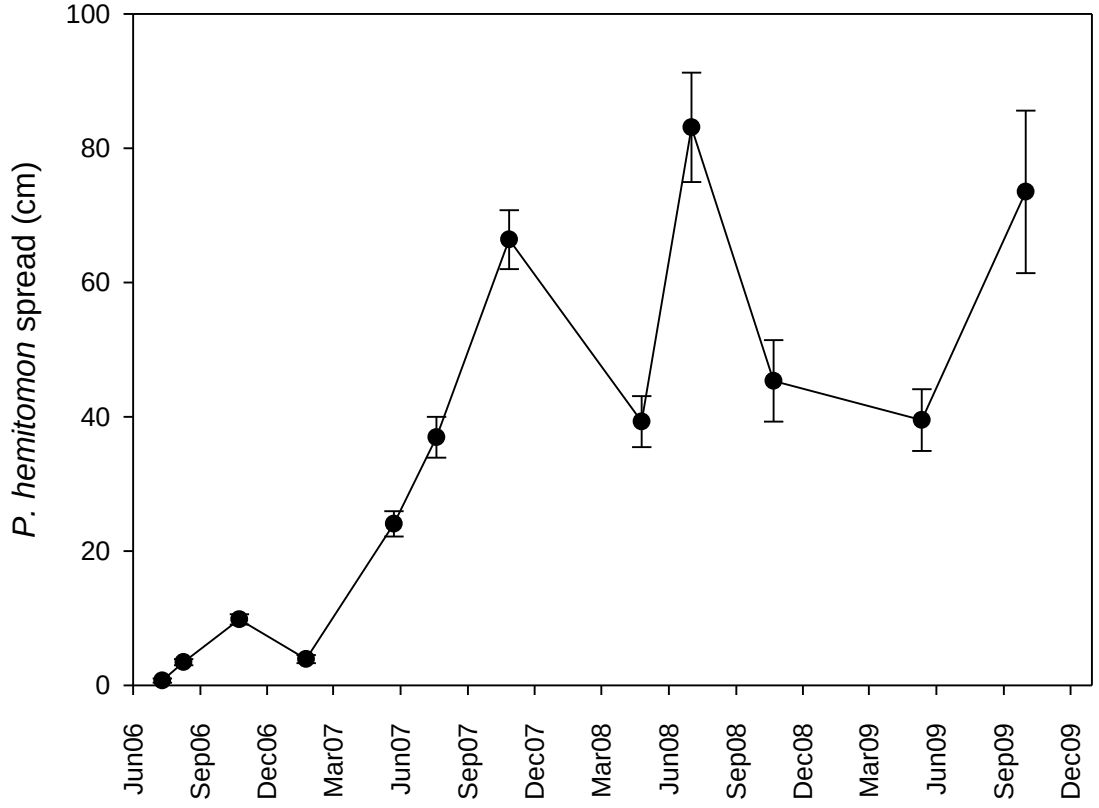

Figure 48. Trends in *P. hemitomon* spread averaged over all monitored structures. Error bars show one standard error.

season with an average spread from all structures of 66 cm. *P. hemitomon* from several structures was interwoven with *P. hemitomon* from adjacent structures especially at sites 1 and 2. Even though *P. hemitomon* cover decreased within the structures during 2008, spread outside the structures increased. These spreading *P. hemitomon* rhizomes do not yet form a cohesive mat and may therefore be less susceptible to grazing. The decline in spread in October 2008, is probably related to the early senescence of *P. hemitomon* related to Hurricane Gustav.

Other species

We observed 40 species other than *P. hemitomon* in the structures and species diversity is increasing (Table 15). However, 7 species were observed in only one survey. Species diversity peaked in July of 2008 and May 2009 at 24 species. *Bidens laevis* was the most frequently observed species it increased in 2007 and remained in 2008 and 2009. *Oxycaryum cubense* was the second most frequently observed species and was most prevalent at sites 3 and 4.

Table 15. Species other than P. hemitomon that occurred in the structures. Numbers are the number of structures in which the species was observed.

Scientific Name	Jul 2006	Sep 2006	May 2007	Jul 2007	Oct 2007	Apr 2008	Jul 2008	Oct 2008	May 2009	Oct 2009	Number of Structures
Alternanthera philoxeroides (Mart.) Griseb.	5	7	38	18	4	49	23	27	52	9	232
Ludwigia leptocarpa (Nutt.) Hara	16	49	4	33	57	2	12	27	3	19	222
Bidens laevis (L.) B.S.P.		5	50	35	76	40	56	33	47	35	377
Oxycaryum cubense (Poepp. & Kunth) Lye	7	34	4		53	7	51	68	27	64	315
Hydrocotyle ranunculoides L. f.	12	1	90	29	13	78	22	11	32		288
Limnobium spongia (Bosc) L.C. Rich. ex Steud.	16	40	31	32	23	37	35			1	215
Eichhornia crassipes (Mart.) Solms			27	19	5	12	27	5	14	2	111
Aeschynomene indica L.		2	1	3	4	1	15	6	1		33
Cyperus odoratus L.	1	16		8	6	4		6		2	43
Leersia oryzoides (L.) Sw.	1		1			1	12	1	4		20
Sagittaria lancifolia L.					1	2	1	2	2	2	10
Thelypteris palustris Schott			2			1	1	1	2	2	9
Salix nigra Marsh.						2	2	2	2	1	9
Panicum repens L.			2	1	1	1		2			7
Vigna luteola (Jacq.) Benth.					1		1	1	1	1	5
Sacciolepis striata (L.) Nash		8			1			12		23	44
Phyla lanceolata (Michx.) Greene						3	10		7	1	21
Cicuta maculata L.						3	7		8	2	20
Paspalum urvillei Steud	1	1	6						4		12
Solidago sempervirens L.					1		1	3	1		6
Baccharis halimifolia L.			1			1	1		1		4
Hydrocotyle umbellata L.							39		24	12	75
Nelumbo lutea Willd.			11	25						2	38
Hydrocotyle umbellata L.			3			7		10			20
Ptilimnium capillaceum (Michx.) Raf.			3			3			5		11

(continued)

Table 15. Continued.

Scientific Name	Jul 2006	Sep 2006	May 2007	Jul 2007	Oct 2007	Apr 2008	Jul 2008	Oct 2008	May 2009	Oct 2009	Number of Structures
Boehmeria cylindrica (L.) Sw.							3		5	2	10
Galium tinctorium (L.) Scop.						5	1		2		8
Kosteletzkya virginica (L.) C. Presl ex A. Gray						1	3			2	6
Sagittaria latifolia Willd.					1		2		1		4
Nymphaea mexicana Zucc.				4		1					5
Amaranthus australis (A. Gray) Sauer								1	1		2
Eleocharis baldwinii (Torr.) Chapman				1				1			2
Unknown dicot						1	1				2
Echinochloa crus-galli (L.) Beauv.	3										3
Habenaria repens Nutt.					3						3
Carex sp.									2		2
Andropogon virginicus										1	1
Fuirena pumila (Torr.) Spreng.							1				1
Symphyotrichum subulatum (Michx.) Nesom				1							1
Typha domingensis Pers.					1						1
Total number of species	9	10	16	13	17	23	24	19	24	19	40

Water Level and Salinity

Malfunction of recording gauges resulted in an incomplete record (Figure 49). However, there were some large fluctuations recorded in salinity, generally correlated with the passage of tropical storms in the fall. The first salinity spike was recorded on October 17 with a maximum salinity of 12.85 ppt measured at the Hanson Canal gauge, followed the next day with a peak of 5.19 ppt at the South Marsh Gauge. Neither the North Marsh nor the Turning-Basin gauges were functioning during this event. The next peak recorded at Hanson Canal at 8.81 ppt occurred on October 8, 2007. However this pulse did not enter the marsh, as salinity remained stable at the other three gauges. The last pulse is related to Hurricane Gustav on September 14, 2008 which significantly raised water level as well as salinity. Water levels peaked on September 14, about 90 cm (3 ft) above the long term average water level at the three functioning gauges (North Marsh gauge was lost during the storm). Salinity peaks were 9.42 ppt at the South Marsh and 7.12 ppt at the Turning Basin.

Of the two gauges most closely associated with the structures the South Marsh had approximately 1 ppt higher salinity than the North Marsh and two peaks raising salinity greater than 5 ppt were recorded at the South Marsh gauge. This indicates that the lower cover of structures by *P. hemitomon* at sites 3 and 4 may be the result of higher salinity at these sites compared to sites 1 and 2.

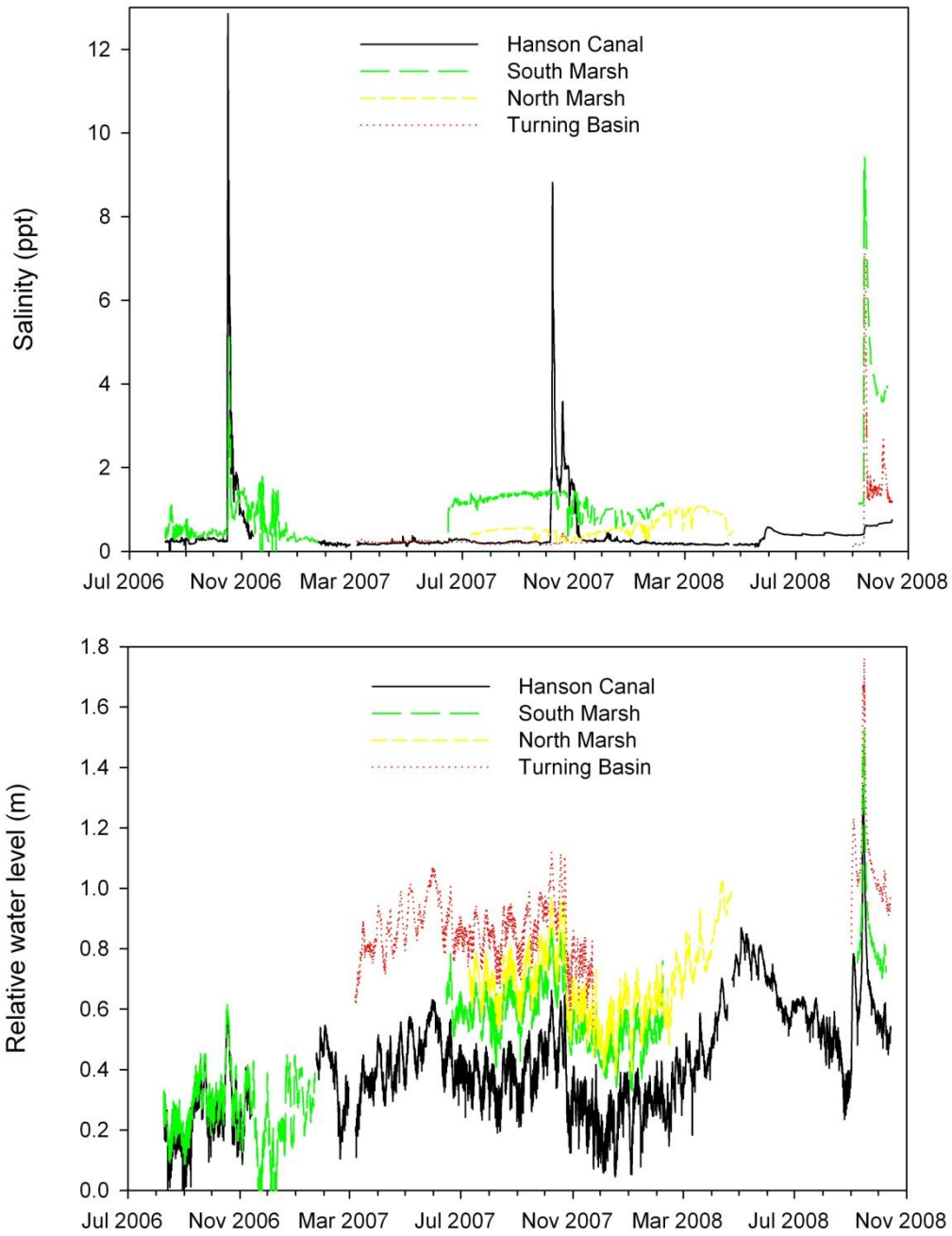

Figure 49. Salinity and relative water level as measured at four locations near the study sites.

FINDINGS

Artificial Floating Marsh Systems Evaluation in Aquaculture Ponds

- Of the 27 structure designs evaluated, only those structures constructed with PVC or bamboo maintained buoyancy.
- *P. hemitomon* cover increased whether established from marsh plugs, whole plants (rhizome and stem material), belowground material, stems, or peat pots. Stems are the most cost effective establishment technique, followed by plants propagated in peat pots.
- Coconut, birch, and coconut-straw mats as well as chicken-wire baskets increased *P. hemitomon* cover. Chicken-wire baskets provide the most cost effective plant material support.

Optimization of Plant Response

- Higher N and P loading rates resulted in:
    - greater aboveground *P. hemitomon* production.
    - greater belowground *P. hemitomon* production.
    - smaller root/shoot ratios (less root allocation per unit of leaf allocation).
    - higher root specific gravity (less buoyant).
- Inundated (15 cm depth) versus saturated (flooded to mat surface (0 cm)) conditions resulted in:
    - decreased aboveground *P. hemitomon* production within the same nutrient loading rate.
    - decreased belowground *P. hemitomon* production within the same nutrient loading rate.
    - higher root specific gravity (less buoyant).
- *P. hemitomon* above- and belowground biomass production exposed to High N loading rates in flooded conditions (inundated) was still greater than the biomass components with low N loading rates in flooded to mat conditions (saturated)
- *P. hemitomon* biomass production was highest on substrates that contained peat.
- *P. hemitomon* biomass production was significantly lower on the birch mat.
- *P. hemitomon* biomass production decreased slightly when planted in combination with other species.
- *L. peploides* was the only species that displayed potential as a secondary species. It has laterally expanding rhizomes that are aboveground and its roots are sufficiently buoyant.
-

Field Deployment

- Establishment with plants in peat pots results in quicker cover increases than establishment from stems. However the stem establishment method although slower is the more cost effective establishment technique.
- All structures remained buoyant and structurally intact in the first two growing seasons. Damaged structures and lack of *P. hemitomon* establishment compromised the structural integrity of the bamboo structures at sites 3 and 4. One string of 10 PVC structures disappeared after Hurricane Gustav. Overall performance of the structures was very good during the 3 years of deployment.

- The expansion of vegetative cover both from plantings and natural succession that occurred outside of the direct footprint of the assembled AFS indicates that the field deployment successfully induced formation of a larger mat system.
- The lower *P. hemitomon* performance at sites 3 and 4 may be related to the slightly higher average salinity and occasional salinity spikes exceeding 5 ppt that occur near these sites.

POTENTIAL OF DEVELOPED TECHNOLOGY TO CREATE FLOATING MARSHES

This floating marsh demonstration project was successful in creating conditions in which maidencane (*P. hemitomon*) growth was sustained and productive, developing a viable floating marsh at the Mandalay field site. This project demonstrated that floating freshwater marsh can be restored in the natural coastal environment by building and deploying artificial floating structures planted with the native grass, *P. hemitomon*. The planted structures performed well through four growing seasons (2006-2009), maintaining structural integrity and productivity, and weathering well intense periods of severe storm and flooding conditions as Hurricanes Gustav and Ike impacted the region in 2008.

Potential to create floating marshes at the local, basinwide, and coastwide scales.
Based on the success of this demonstration project, our findings indicate that this developed technology has an excellent potential to create freshwater floating marshes at the local, basinwide, and coastwide scales. There are about 1 million acres of fresh water marsh in the Louisiana coastal area (Figure 50). Many of these freshwater marshes, particularly in the deltaic plain, are in degraded condition with remaining marsh interspersed with shallow open water areas. There is tremendous potential for implementing the techniques developed in this demonstration project to achieve floating marsh creation in these areas at all scales.

The demonstration project utilizes small, self-sustaining modules (AFSs) as the fundamental restoration unit. Each module becomes a viable building block for a larger sustainable created marsh, as each module contains sustainable plant material within its floating structure. The individual AFSs are readily connected together into larger assemblages to form large or small formats that will fit the needs of any particular marsh creation candidate.

Coastwide Scale
On a coastwide scale, open water within wetland areas that remain fresh throughout the year and are surrounded by freshwater vegetation are potential areas for floating marsh creation using the technique developed in this demonstration project. The distribution of the approximately 1 million acres of freshwater marsh areas in the Louisiana coastal area are indicated in Figure 50. Most of the fresh marsh areas noted, other than the active deltas receiving high mineral input (Atchafalaya Delta, Wax Lake Delta, Mississippi River Delta), have high potential for restoration.

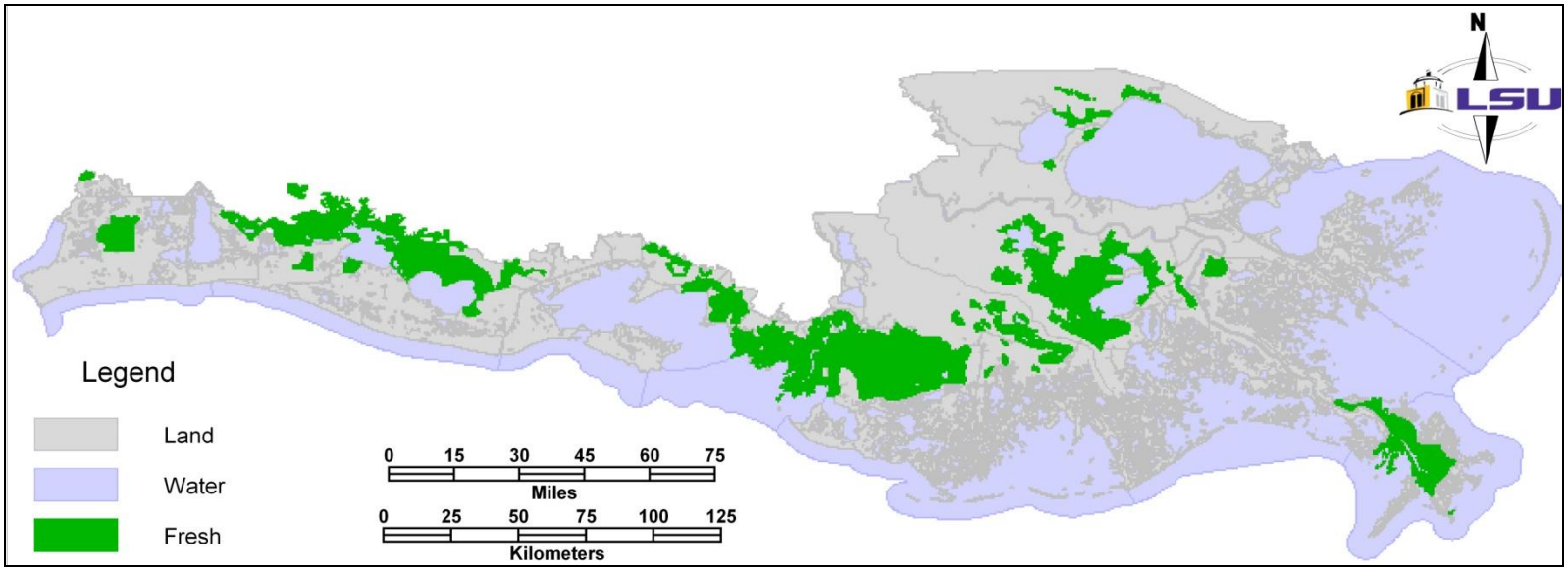

Figure 50. The Louisiana coastal zone depicted with an overlay of fresh areas as determined in 2007 (Sasser et al 2008). The green areas represent possible areas for deployment of Artificial Floating Structures (AFS).

Basinwide Scale

The northern reaches of Louisiana coastal basins are typically freshwater areas, much of which are in a degraded condition with large open water areas. At the basin scale, key elements of restoration are to decrease the area of the open water within large water bodies to reduce fetch and thereby wind-driven waves, and to protect shorelines to eliminate or decrease ongoing erosion. The freshwater marsh areas in Terrebonne Basin are indicated in Figure 51, as an example of the distribution of potential restoration areas at the basin scale.

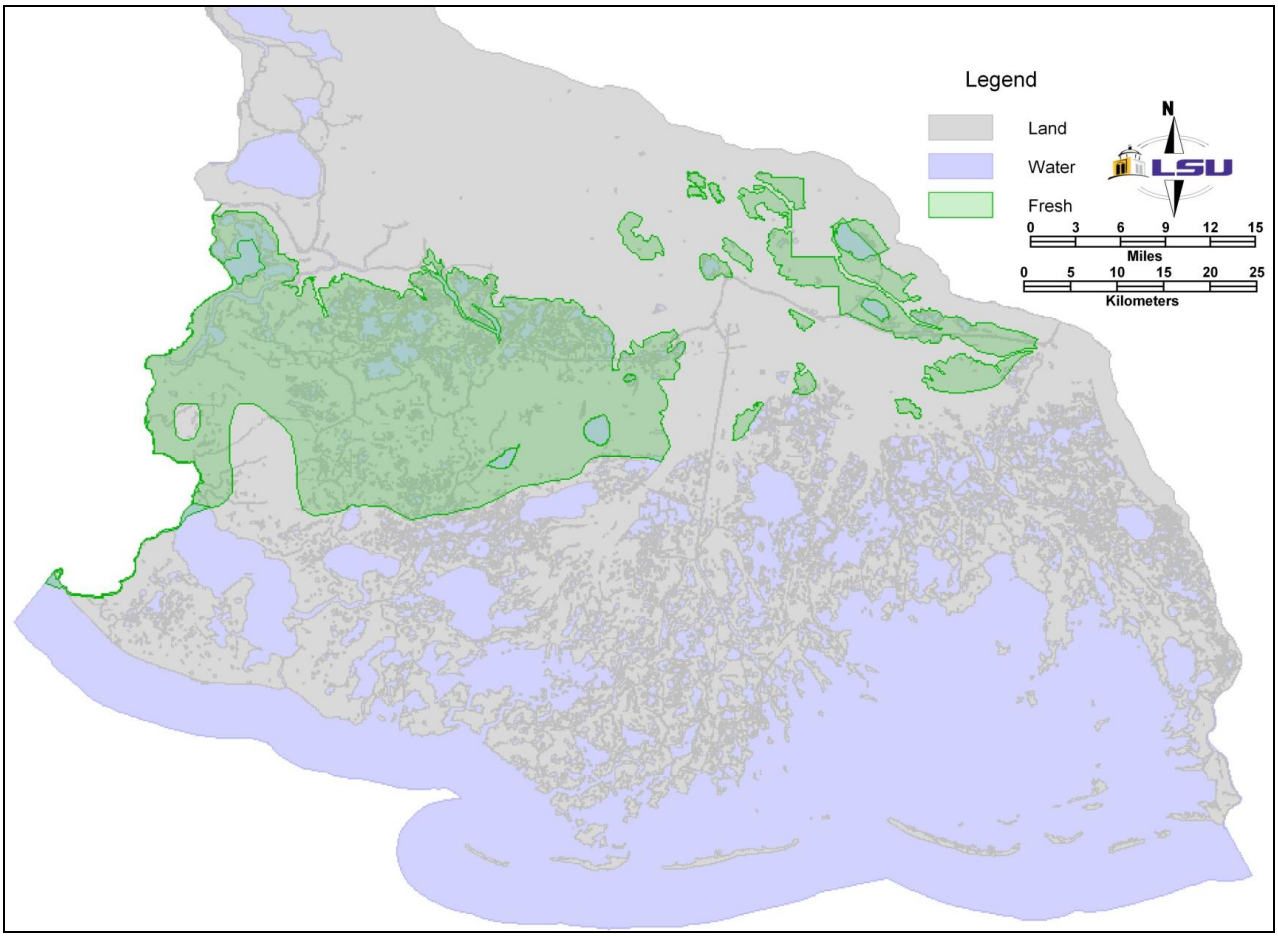

Figure 51. Terrebonne Parish land and water with an overlay of fresh marsh in green as determined in 2007 (Sasser et al 2008).

Local Scale

At the local scale, open water areas such as ponds, small lakes, canals, and open water within degraded marshes could be revegetated and restored using assemblages of the basic floating island modules. The size of the area to be restored and the funding available would drive the number of units assembled together. Considerations in designing the layout of a particular restoration site would include protecting existing marsh shorelines from erosion, decreasing open

water areas within water bodies undergoing restoration to reduce wave action (e.g. reduce fetch), and providing adequate vegetated structures to grow new marsh. Linear rows of the modules aligned adjacent and parallel to existing eroding shorelines should effectively protect and minimize erosion at the shoreline (water and marsh interface). The layout for this feature is illustrated in Figure 52a through d. Linear rows of modules can also effectively divide larger areas of open water into smaller compartments, creating a landscape of smaller water bodies with less wave energy. An example of this configuration that divides larger open water into smaller water bodies is illustrated in Figure 52b. The layout for any individual restoration site should take advantage of the natural landscape to connect shorelines in an efficient manner, for instance cutting off existing coves to produce smaller water bodies, and connecting land features across water bodies at narrow points. In a similar fashion, ponds and lakes could be divided and subdivided using linear rows of modules to create smaller water bodies (Figure 52c). Within the smaller water bodies, linear rows or multiple rows forming grids of floating modules that are appropriate to the shapes of the individual water bodies could be deployed to establish the nucleus of new marsh that would expand over time and connect and intermesh with other natural or restored marsh units (Figure 52d). The technique can also be used to restore abandoned canals, as illustrated in Figure 53a through c.

RECOMMENDATIONS

This demonstration project was successful in creating floating marshes. The artificial floating islands vegetated with maidencane are assembled from modular units to create the appropriate size required for a particular project need. We recommend that this technology be used immediately to develop CWPPRA coastal restoration projects in suitable fresh water marsh areas. We recommend the method tested in this demonstration be used in large and small scale coastal restoration projects. A desirable element of this technology is that it can be carried out at any scale, depending upon the specific need and funding support available. The method can be used in open water conditions and degraded fresh water wetlands. Both bamboo and PVC material worked well to provide the buoyancy necessary for the floating structures to be successful in floating marsh creation. However, we recommend using bamboo as the first choice in the structures whenever possible because it is a natural, renewable, and biodegradable material. Maidencane plant material was highly effective in growing robust, productive maidencane marsh mats within the floating structures. Both potted maidencane plants and cut stem material were highly successful as the source material for new plant growth. We recommend using stem material because the cost is considerably lower. One consideration is that stem material needs to be deployed within 24 hours of harvest to avoid desiccation of the stems. Potted plants, although more expensive, may survive transportation and storage better. So the choice of material is dependent on the logistics of site accessibility.

We specifically recommend implementing a coastal restoration project through CWPPRA to restore freshwater degraded marsh. A project using methods developed in this demonstration project was submitted as a proposed project in PPL 20 by NRCS to restore freshwater marsh in northwestern Terrebonne Parish. This proposed project (Lake Hackberry Northeast Floating Marsh Restoration) was not selected and funded, but we highly recommend that funding should continue to be solicited for this and similar restoration projects to create or enhance floating

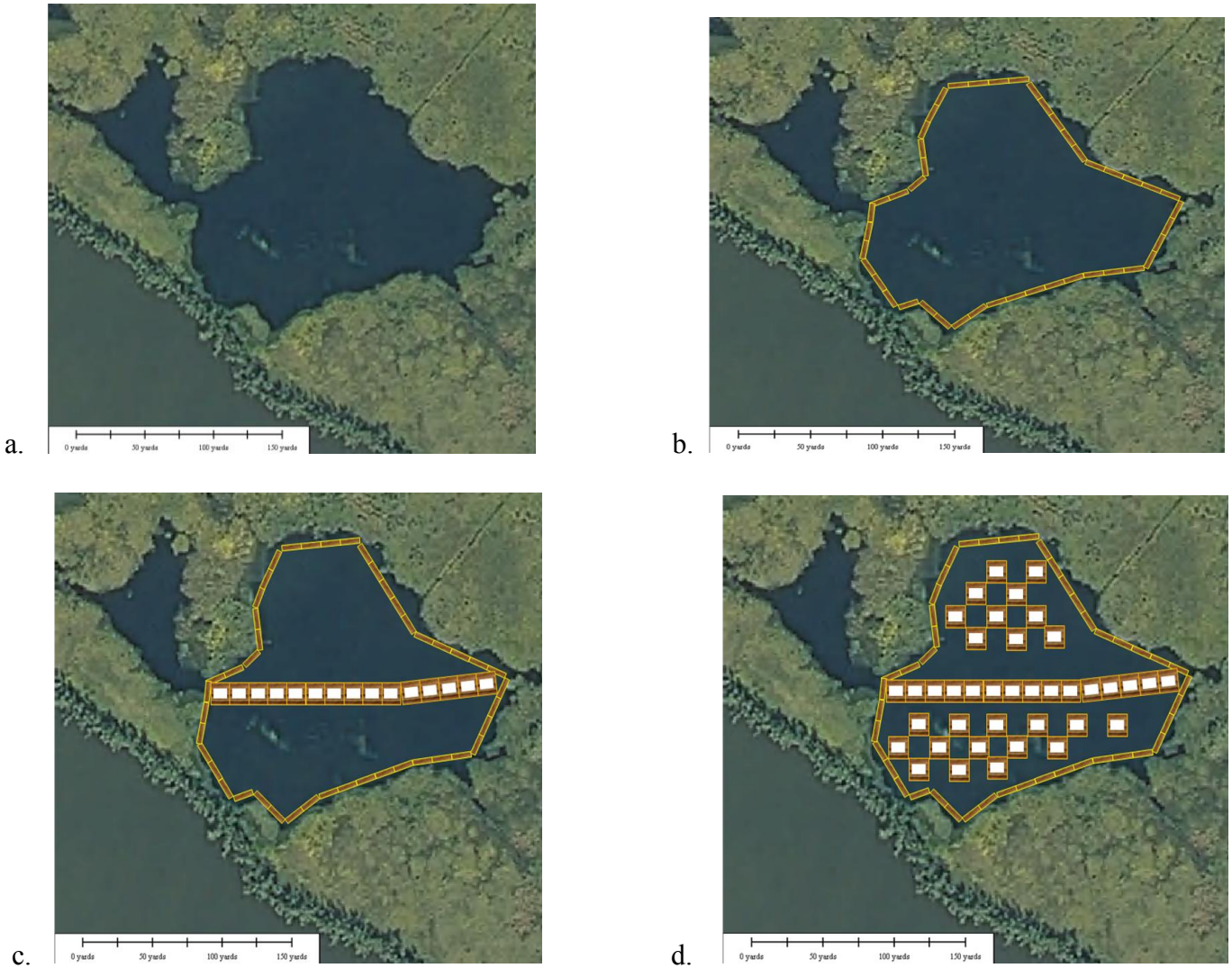

Figure 52. Panel a shows an example of a pond surrounded by fresh marsh that could be filled with Artificial Floating Structures (AFSs). Panels b through d show a progression of filling in the pond, from using a single row of AFSs along the shoreline to minimize erosion (b). Panel c depicts the use of double rows of AFSs to break up the large open water into two smaller ponds. Panel d depicts the filling in open water areas with a pattern of double rows of AFSs.

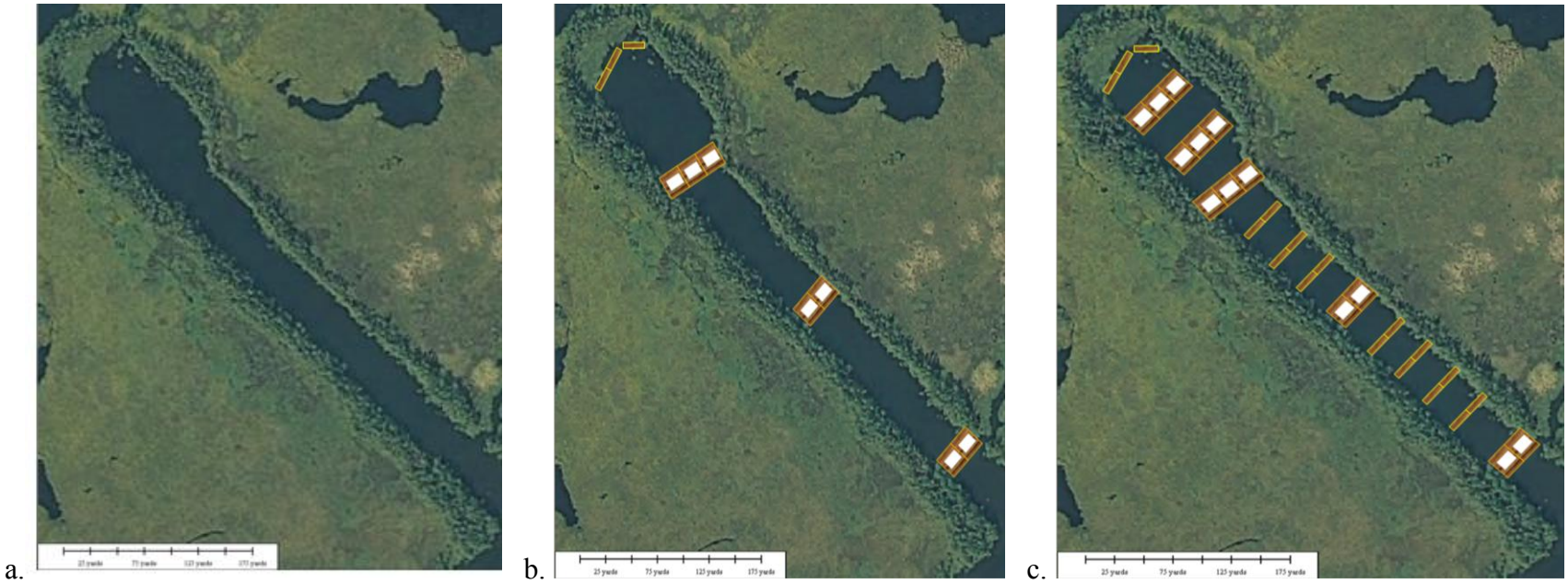

Figure 53. Panel a is an example of an abandoned canal surrounded by fresh marsh that could be filled with Artificial Floating Structures (AFSs). Panels b and c show a progression of filling in the canal. Panel b depicts single rows of AFSs along the shoreline of the canal with no spoil banks and using double rows of AFSs to break up the large open water into three smaller ponds. Panel d depicts the filling in of the open water areas with a series of single rows of AFSs.

marshes in degraded freshwater environments using the methods developed in this demonstration project. We also recommend implementation of smaller-scale projects using the demonstration project methods. This technique should be successful in restoring floating freshwater marsh in habitats such as degraded freshwater marshes with small ponds and water bodies in areas with low hydrologic energy. Plant species other than *P. hemitomon*, such as *L. peploides*, may be suitable for use in marsh creation and further investigations should be conducted to determine usefulness of appropriate plant species.

Our recommendations from this demonstration project are specific to areas with freshwater conditions and little or no salinity influence throughout the year. However this technique could potentially be effective in marsh areas influenced by salt water if different plant species suitable for those conditions are used. We recommend an additional effort is funded to determine the effectiveness of restoring marsh using this technique, with other plant species that tolerate salinity influence, such as *Schoenoplectus americanus, Spartina patens, Phragmites australis*, etc.

Specific Recommendations

The marsh creation technique developed in this demonstration project should be tried at a larger ―project" scale to further determine its success and refine the methods. We recommend developing restoration projects to restore shallow open water areas within degraded freshwater marshes, abandoned canals, and other appropriate open water bodies. Some specific recommendations relative to future project implementation are provided below.

Materials

We recommend using dimensions of 4ft by 8ft for the artificial floating structures, although other dimensions could easily be used as well. These dimensions provide adequate area for plant production, are a reasonable size structure to deploy, and provide efficiency in use of construction materials.

We recommend using bamboo material to provide buoyancy in the floating modular structures. Bamboo is a natural product and is biodegradable. Our floating structures in this demonstration project were successful using bundles of bamboo poles fastened together for buoyancy. We recommend using 2 8- foot long, 3-inch diameter bamboo poles grouped and bundled together along each side of the AFS to provide adequate buoyancy for each floating structure.

Nutria control must be provided in a successful freshwater marsh creation project. We recommend that nutria control be accomplished through trapping and hunting techniques, or an extension of the CWPPRA nutria control program. Building nutria control coverings on each individual floating structure is effective in controlling nutria, but adds significant weight to the structures and increases the costs.

We estimate that the total cost of construction materials for a single 4ft x 8 ft structure is approximately $42, and the time required to assemble a single structure is approximately 1 hour. not including addition of vegetative material and associated labor. See Table 16 for a listing of structure components and estimated costs based on Kinler (2010) which were related to building and deploying floating structures for the PPL20 Lake Hackberry Northeast Floating Marsh

Restoration project proposed in 2010. The estimates provided in Table 16 represent the best estimates of component costs available at the time of proposal development. For the purposes of this report, the Kinler (2010) estimate serves as an example of the estimated costs of restoration units for a marsh restoration project using the floating marsh creation technique developed in this demonstration project.

The summary costs in Table 16 are based on using maidencane potted plant material, however as we stated earlier, stem material from maidencane plants can be used to establish vegetation growth within floating structures under the right circumstances at a significantly reduced cost. Both potted maidencane plants and cut stems were successful in establishing plants within floating structures in the demonstration project, however stem material is less expensive. It can be harvested from healthy marshes like those at Lacassine NWR or taken from potted lants. In addition, stems are lighter and occupy less volume during transport. We do not have a cost of stem material. However, we estimate the cost of such material to be approximately 25%-50% of the cost of potted plants.

The anchoring system utilized in the demonstration project consisted of strong wooden posts driven into the substrate, with the floating structures attached by rope to the posts. This technique worked very well, with less than 10% loss due primarily to Hurricanes Gustav and Ike. Therefore, we recommend this technique for future projects. The sizes and costs of the posts and ropes may vary depending upon the size and number of modules used and the local soil/foundation conditions, and should be determined for each application with the assistance of appropriate technical expertise (e.g. engineers).

Layout

We recommend that the configuration of floating structures deployed at a marsh creation site be designed to fit the particular attributes of that site. Our general recommendation is to use a single row (Figure 53; the ―single" row is a set of 3 linear rows of structures, with each row made up of five 4ftx8ft structures attached together) adjacent to shorelines to stop or minimize erosion; use a double row (Figure 54: a double row is made up of 2 sets of ―single rows" desribed above) to divide large open water areas into smaller compartments; and use as many additional rows as funding allows within the open water areas to create new marsh.

Deployment

Mobilization and installation logistics will vary depending upon the location and size of the project, and solutions to these variables should be determined to fit the specific project needs. For the demonstration project, structures were assembled at the dock and transported to the field site by small boat. For a large project and field sites that are more remote, transport of structures would likely require using a small barge which would also provide a staging platform at the field site. The logistics and cost efficiencies should be worked out based on the needs for each individual project.

Based on the results of the demonstration project and subsequent experience, we recommend late winter/early spring (March/April) as the best months of the year to deploy vegetated floating structures in marsh sites needing restoration. The rate of growth in early spring facilitates more rapid mat development, and maximizes growth and expansion of the vegetation and marsh root

mat. Vegetated structures set out later in the summer exhibited sustained growth, but vegetation growth was not as robust and productive.

Table 16. Summary of materials and estimated costs for assembling a 4ft x8ft structure (from Kinler, 2010).

Component	Description	Unit	# units	Cost/Unit	Cost
Bamboo poles for buoyancy	3 in diameter poles	ft	32	1.00	$32
Cross brace	6 ft wooden fence board	ea	4	0.75	$2
Wire	Wire for fastening	Linear ft	24	0.10	$2.40
Bottom	Poultry Netting (wire)	Sq ft	64	0.08	$5.12
Assembly Labor		Hours	1	$15.00	$15.00
Vegetative Material	4 in pots of P. hemitomon	Pot	10	$2.50	$25.00
Vegetation Assembly Labor		Hours	0.5	$15.00	$7.50
Total					$89.02

Additional materials required for deployment in shallow water degraded marsh environment:
Posts - 4”x4”x16’ treated wood @ $15
Rope – 3/8” polypropylene @ $0.24/linear foot

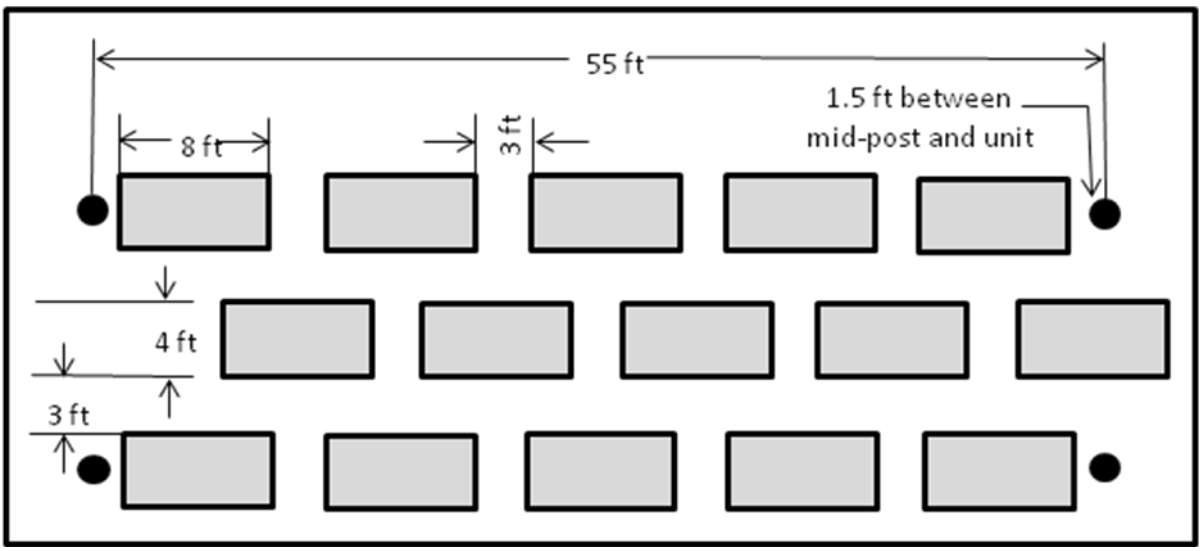

Figure 54. Dimensions of a single row of Artificial Floating Structures.

Maintenance

Our expectation is that the floating structures will develop a viable vegetation mat with productive plants that should provide a sustainable floating mat within two to three growing seasons. Maintenance costs should be low, providing the floating structures are not impacted and damaged by tropical storms, boat strikes, etc. We estimate that < 10% (30 out of 300 structures) of the demonstration project materials were damaged over the 4 year period of deployment, and we expect that components of future projects using this technique would have a similar response to environmental conditions over the 20 year period of the restoration project.

Monitoring

Monitoring associated with the demonstration project included periodic observations of species composition, lateral expansion of vegetation, condition of structural components, grazing issues, etc. (one O& M survey per year, vegetation surveys every three years). This level of monitoring seems appropriate to provide information relative to a restoration project using methods similar to those in the demonstration project. For large restoration projects, utilizing marsh area measurements derived from aerial photography such as often used in CWPPRA project monitoring would be appropriate.

Expected Benefits

We expect that a project implemented in a freshwater area using the techniques developed in this demonstration will be effective in establishing new freshwater marsh in open water areas associated with degraded freshwater marsh in coastal Louisiana. We estimate that the mats will extend at least 15 cm/year. It is worth noting that individual rhizomes from the mats extended much further than that, and could potentially increase the expansion rate as individual mats merge together. Placement of structures will determine how quickly the area between the mats will be filled in.

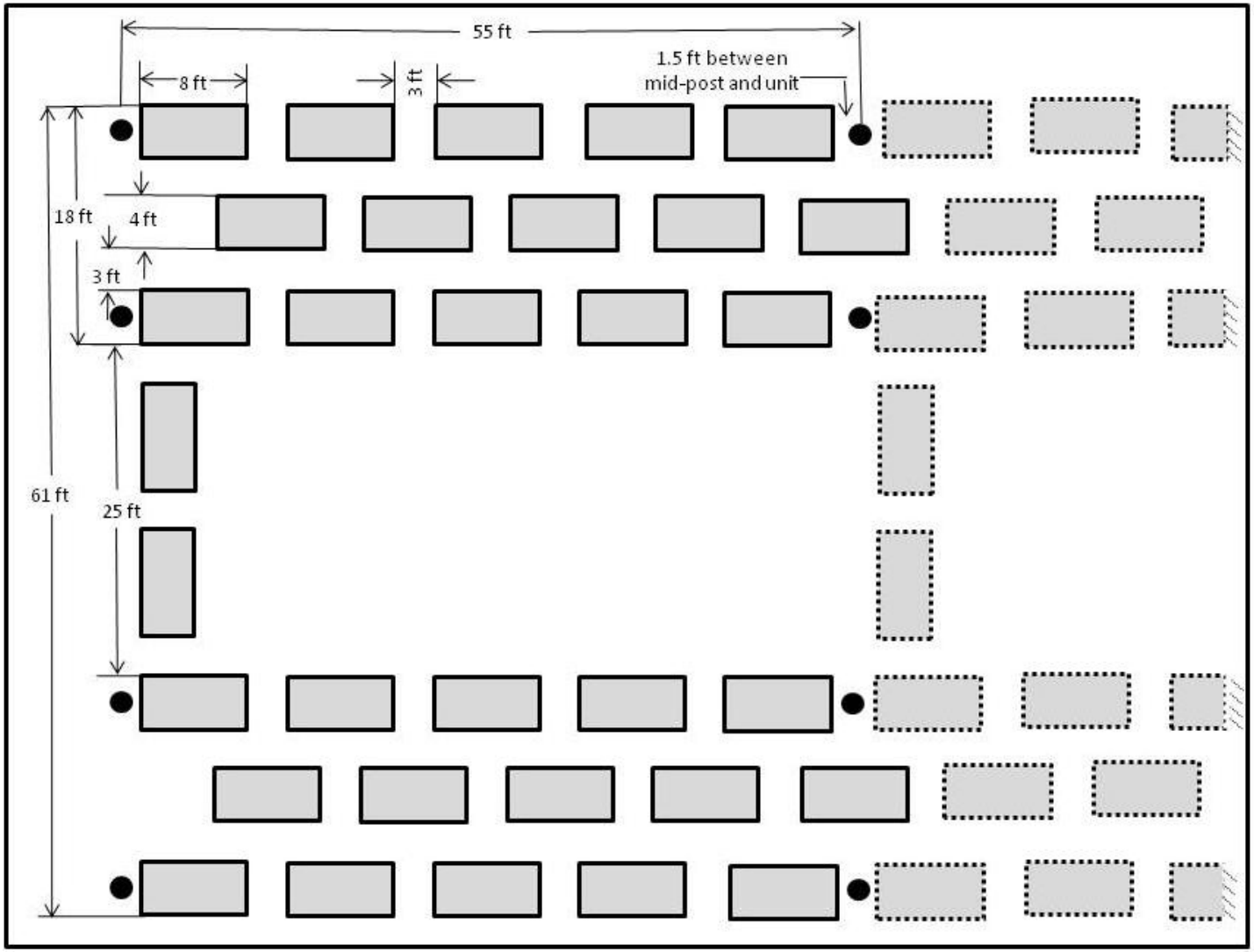

Figure 55. Dimensions of a double row of Artificial Floating Structures.

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APPENDIX A

Overview of Artificial Floating Systems Tested at Ben Hur Aquaculture Ponds July 2004 - October 2005

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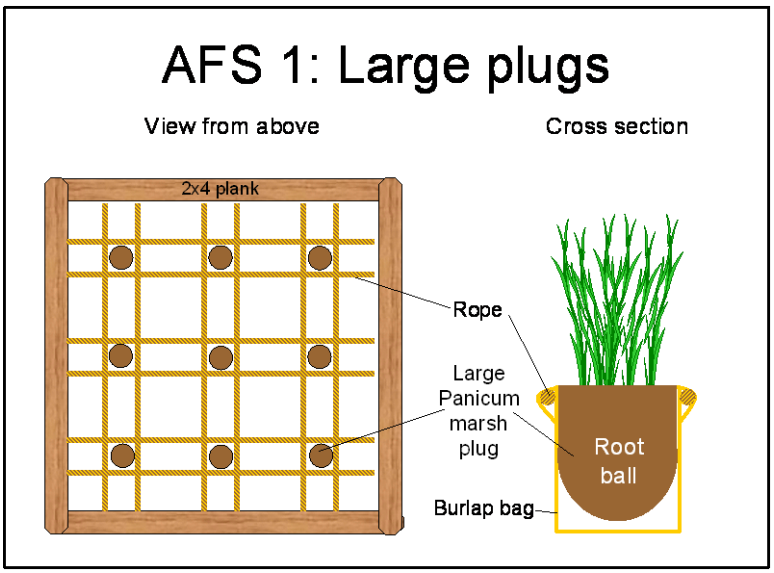
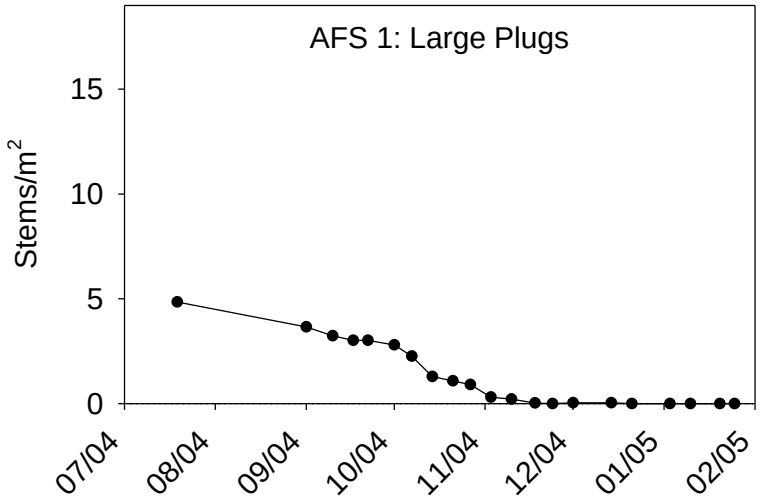
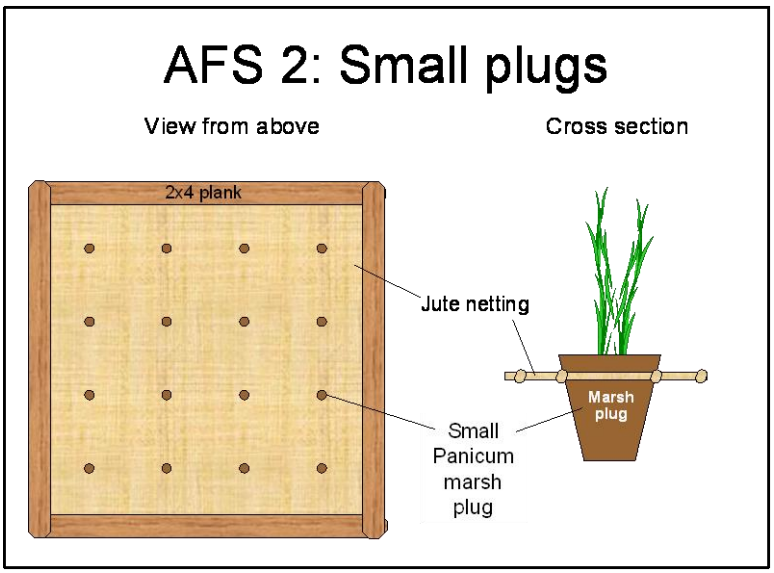


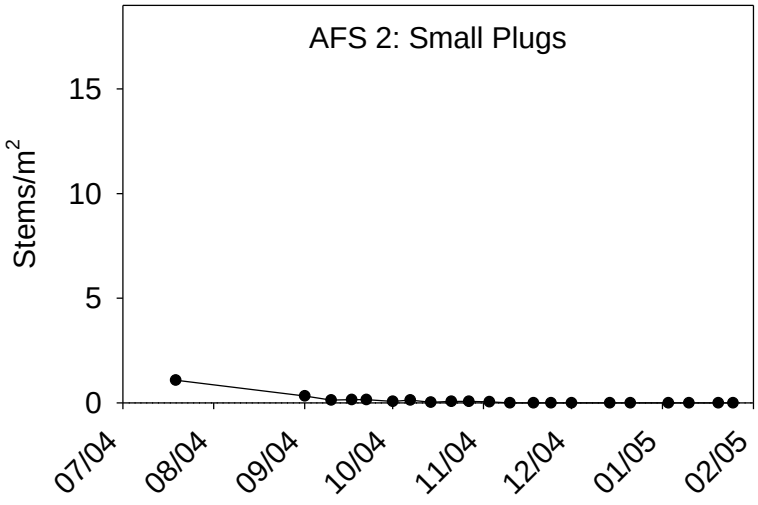
Artificial Floating Structure 1

The design for this AFS provides a structure that evenly spaces "large" (~5 gallon bucket) plugs of *P. hemitomon.* This AFS is approximately 3 m (10 ft) on each side and contains 9 large plugs. The frame was constructed with buoyant wooden planks and plugs were evenly distributed within the frame using cotton ropes. The plugs will be kept in place using burlap sacks that are attached to the ropes.

This picture shows AFS 1 near the peak of its performance on September 22, 2004. Soon after, all plugs were heavily grazed. No living vegetation was observed in these structures from early November 2004. Four of the structures have remained floating. One structure partially submerged during the winter months. By the end of February, the burlap bags and some of the ropes were starting to deteriorate. It is not possible to fence these structures to exclude nutria and muskrat, due to the large holes on the bottom that provide easy access for aquatic herbivores. These structures were removed from the ponds in March 2005.



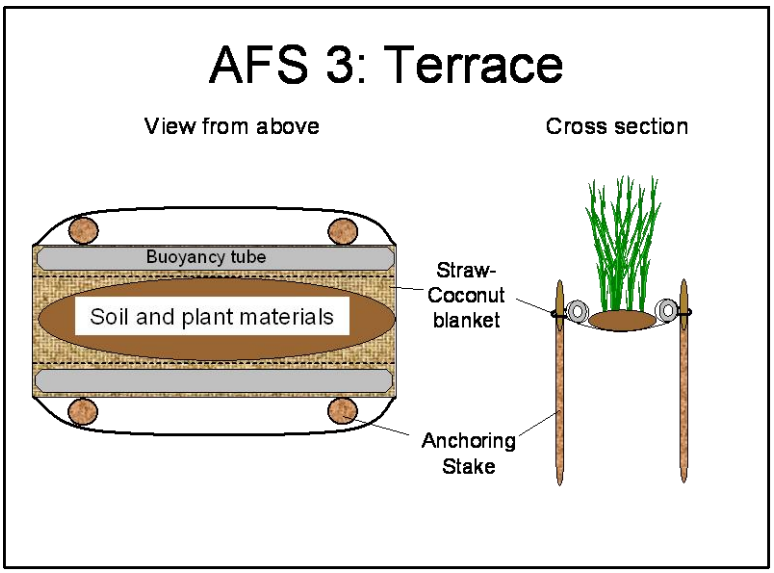




Artificial Floating Structure 2

The design for this AFS provides a structure that supports small plugs of *P. hemitomon* marsh. This AFS is approximately 3 m (10 feet) on each side and contains 16 small plugs. The frame was constructed with buoyant wooden planks and plugs were evenly distributed within the frame using a loosely woven jute material.

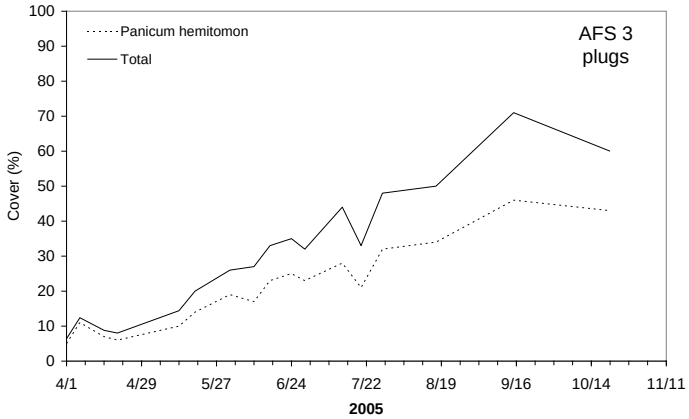
At the time of deployment it became apparent that additional bracing was necessary because of excessive sagging of the jute netting. This cross bracing can be seen in the picture. Vegetation never really established in these structures and the jute netting started to deteriorate approximately 2 months after deployment and no material was left by the end of February. Four of the structures remained floating and one has been submerged floating since early September. Because of the poor performance these structures were removed from the ponds in March 2005.

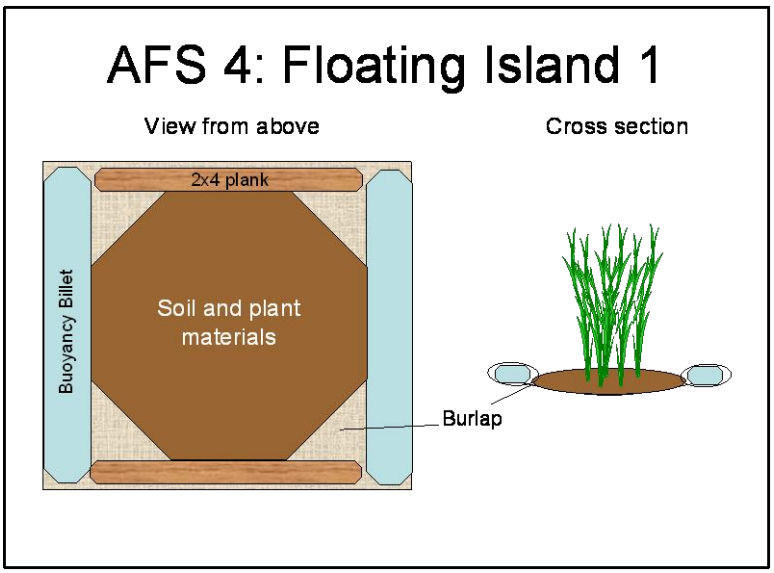


Artificial Floating Structure 3

The design for this AFS consists of a hammock like containment system, filled with substrate and planted with nursery grown *P. hemitomon*. This AFS is approximately 3 m (10 ft) long and 1 m (3 ft) wide. The hammock was constructed using North American Green SC250, a 70% straw-30% coconut fiber matrix incorporated into a permanent three-dimensional turf reinforcement matting. Each side of the straw-coconut fiber hammock was made buoyant using a buoyancy tube (4ft.x10ft. 4 inch PVC pipe filled with marine foam). The hammock was filled with a 5 cm (2 in) layer of organic soil material and planted with 10 *P. hemitomon* plants (small nursery stock).

All of these structures have been floating at the surface. The coconut-straw mat has remained in place although some of the organic mat material is disappearing. These structures were relatively well vegetated during the early fall of 2004. Although these structures were grazed, grazing pressure seemed lower than on some of the other structures. However, to improve vegetation establishment, these structures were replanted with 10 marsh plugs and fences were added to the structures in March 2005. The added plugs remained in good condition through the end of the growing season and *P. hemitomon* cover has increased from 5% on April 1 to a maximum of 46% on September 15, 2005.

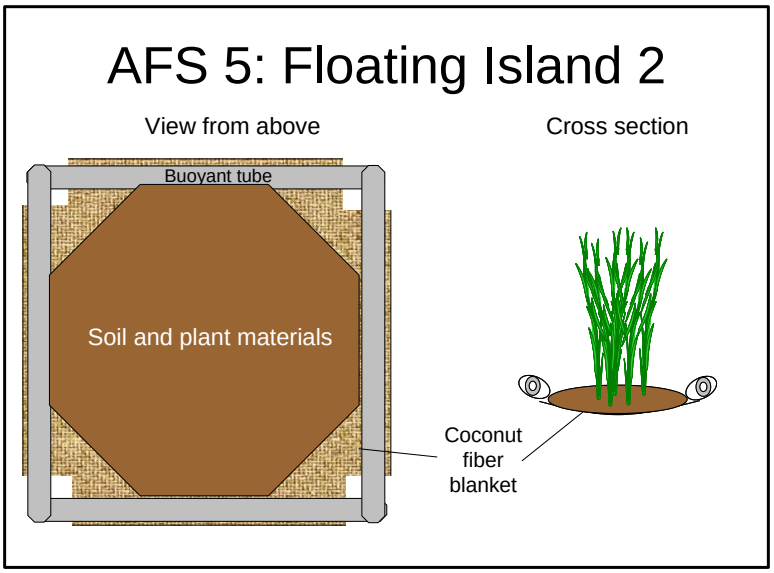


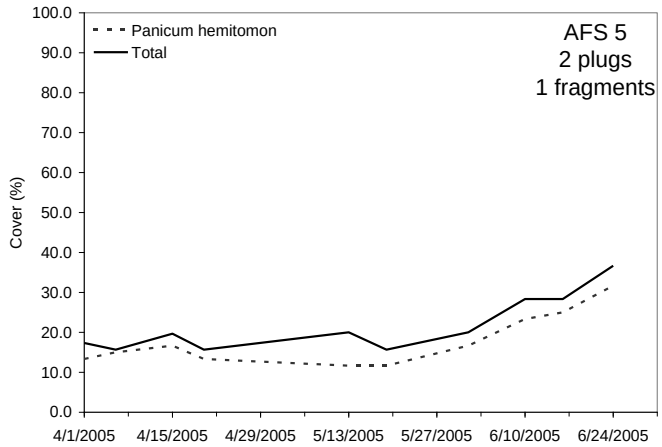


Artificial Floating Structure 4

This design used commercially available buoyancy billets (for floating dock construction) for flotation that were kept separated with wooden planks with a burlap hammock topped with 5 cm (2 in) of organic soil and planted with 20 *P. hemitomon* plants. Structure dimensions 3 x 3 m (10ft.x10ft.).

Structures attracted grazers and burlap deteriorated as a result. Plants never really got established in these structures as demonstrated by the top picture from September 22, 2004. Because these designs lost their structural integrity as demonstrated in the bottom picture from October 31, 2004, they were removed from the ponds in October 2004.

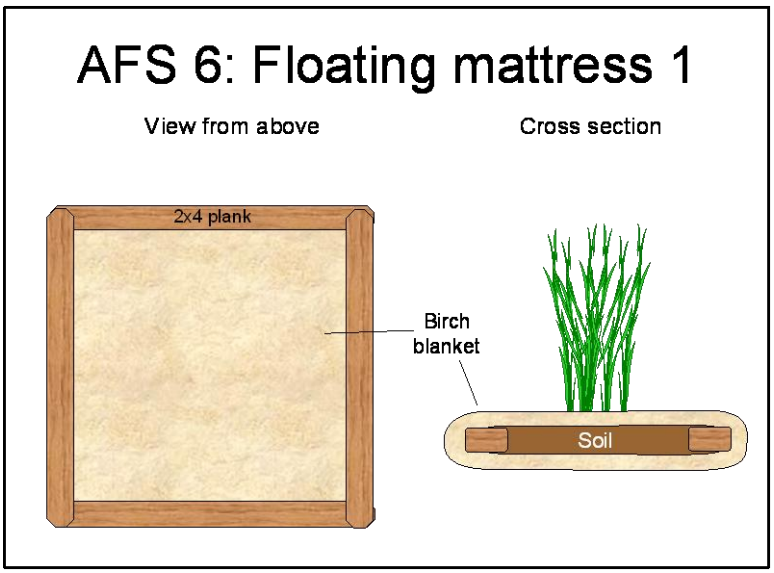




Artificial Floating Structure 5

This design consists of four approximately 3 m sq. (10 ft) 4 inch diameter PVC tubes filled with closed cell Styrofoam that support a coconut fiber fabric topped with 5 cm (2 in) of organic soil and was planted with 20 *P. hemitomon* plants (small nursery stock). The coconut fiber mat used for this design consists of two layers of the North American Green C125, a 100% coconut fiber with a functional longevity of approximately 36 months.

These structures were floating at the surface through early December, when one of them partially submerged. Vegetation did relatively well in these structures during the early fall. Fences were added to these structures in October 2004. However, by the end of February very limited resprouting of the vegetation had been observed. Because the coconut mat was still in good condition, two of these structures were replanted with plugs, and one with shredded plugs in March 2005. The fourth structure, which partially submerged was removed. All the transplanted material has remained in good condition but *P. hemitomon* cover remained more or less stable at 13% through May, but increased to 32% by June 24, 2005. Monitoring of these structures stopped in July.



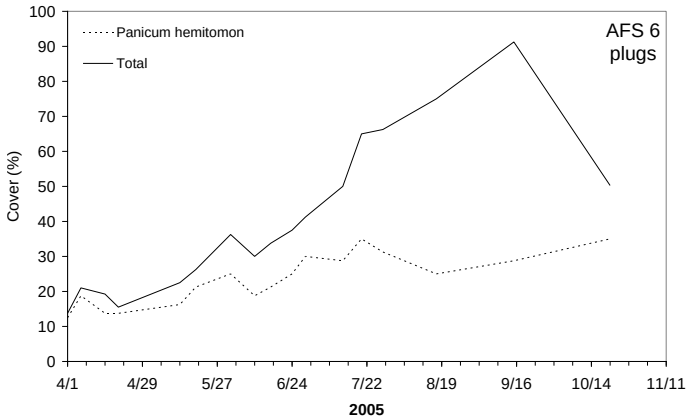
Artificial Floating Structure 6

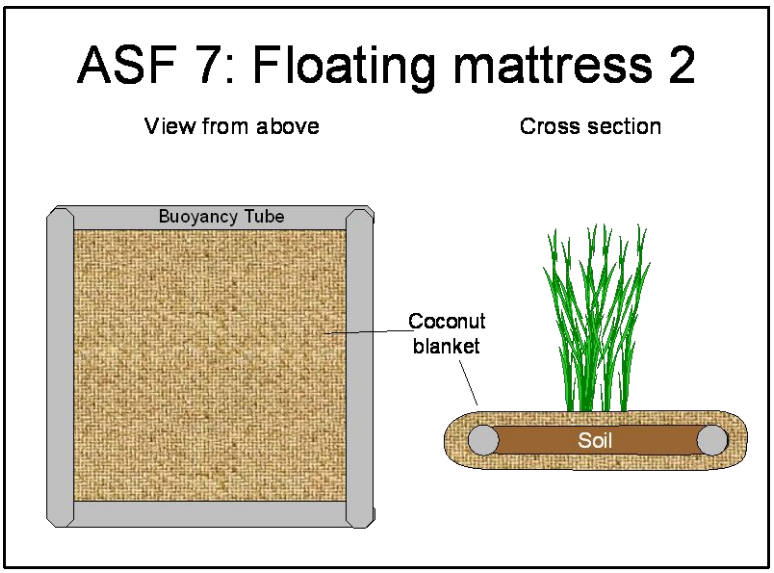
This design created a piece of floating marsh by sandwiching about 5cm (2 in) of organic soil material between two birch fiber blankets (Western Excelsior SD-3). Rigidity and buoyancy were achieved with a wooden frame that was 1m by 1 m (4 x 4 ft). The mattress was planted with 10 *P. hemitomon* plants (small nursery stock).

All structures have been floating at the surface. Structures were fenced and replanted in October 2004. The birch mat has remained in excellent condition. Vegetation died-back during the winter months, but started increasing in February 2005. However, in order to improve vegetation establishment, these structures were replanted with 5 marsh plugs in March 2005. Average *P. hemitomon* cover was 12% on April 1, 2005, and reached a peak of 35% by July 20, 2005. Other species, especially, *Ludwigia* sp. out-competed *P. hemitomon* in the late growing season.

AFS 6 on April 1, 2005

AFS 6 on August 22, 2005





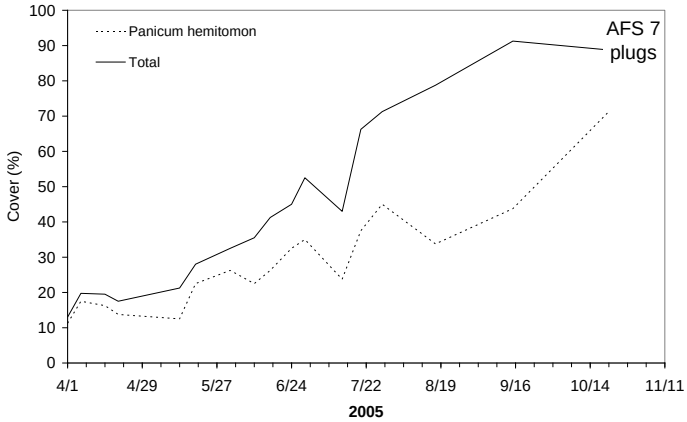
Artificial Floating Structure 7

This design created a piece of floating marsh by sandwiching about 5cm (2 in) of organic soil material between two coconut fiber blanket (Western Excelsior CC-4). Rigidity and buoyancy were achieved with a 1 inch PVC frame that was 1m by 1 m (4 x 4 ft x 1 in. PVC). The mattress was planted with 10 *P. hemitomon* plants (small nursery stock).

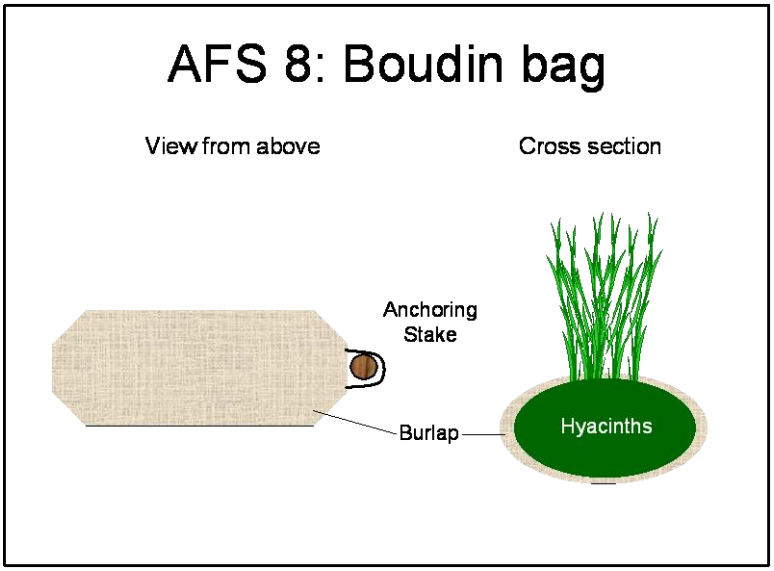
All structures have been floating at the surface, except for one structure that sunk in September 2004 and was removed from the pond. Structures were fenced and replanted in October 2004. The coconut mat has remained in excellent condition. Vegetation died-back during the winter month, but started increasing in February 2005. However, in order to improve vegetation establishment, these structures were replanted with 5 marsh plugs in March 2005. The added plugs remained in good condition through the end of the growing season and *P. hemitomon* cover has increased from 11% on April 1 to 71%. Although other species occurred in these structures, they never out competed *P. hemitomon*.

AFS 7 on April 1, 2005

AFS 7 on August 22, 2005

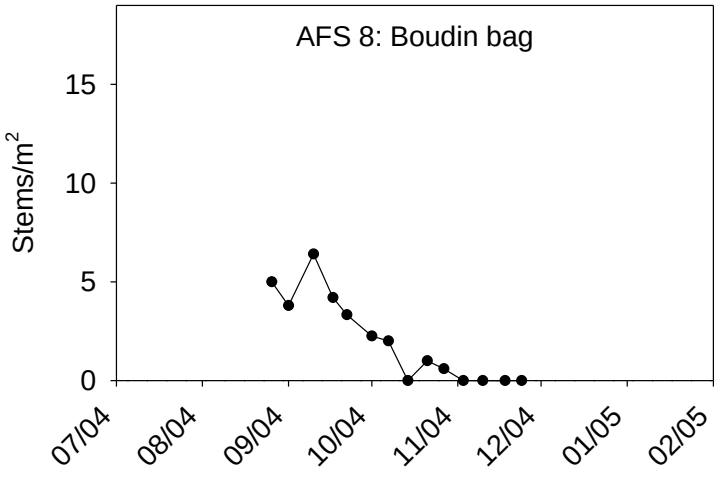


Artificial Floating Structure 8

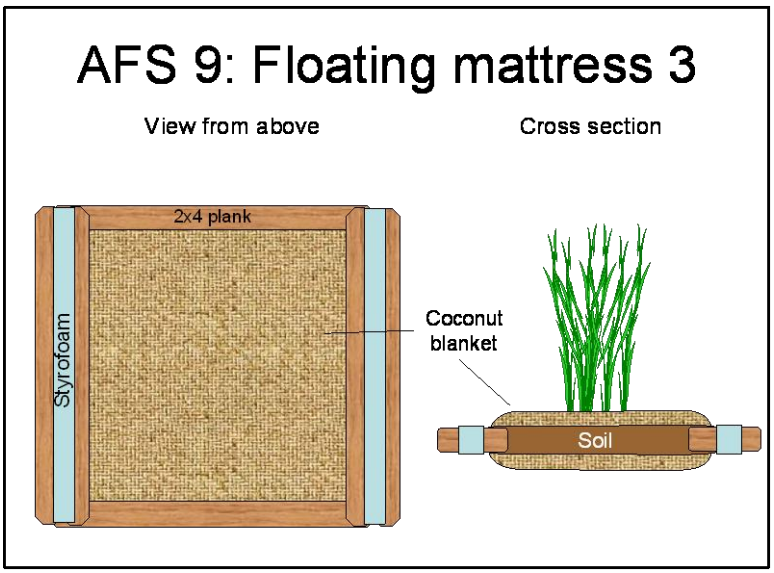


A bag was constructed from burlap material and filled with water-hyacinths. The bag was 1 m by 1m (4 x 4 ft) and was planted with 10 *P. hemitomon* plants (small nursery stock).

The plants on these structures were grazed and the structures showed erratic floating behavior during the fall of 2004. All structures sank with colder temperatures at the end of November 2004. None have re-emerged by March 2005.

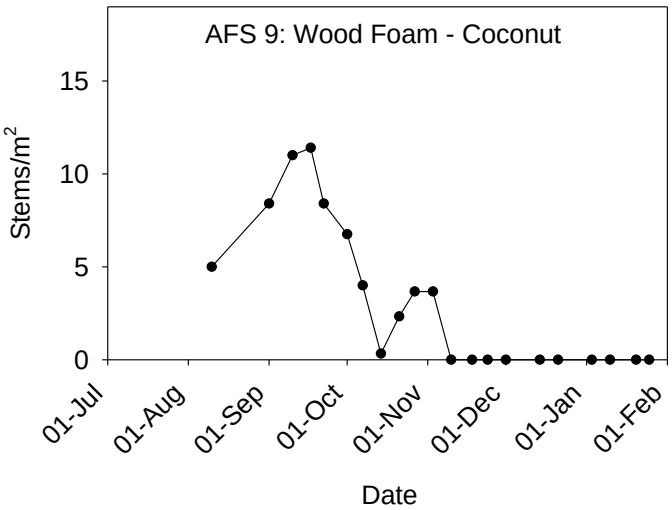


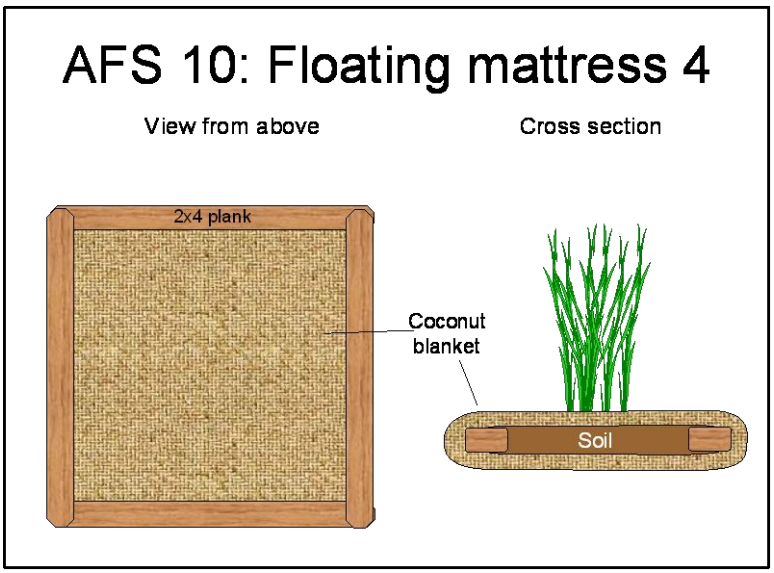
Additional Designs Started in the Fall of 2004



Artificial Floating Structure 9

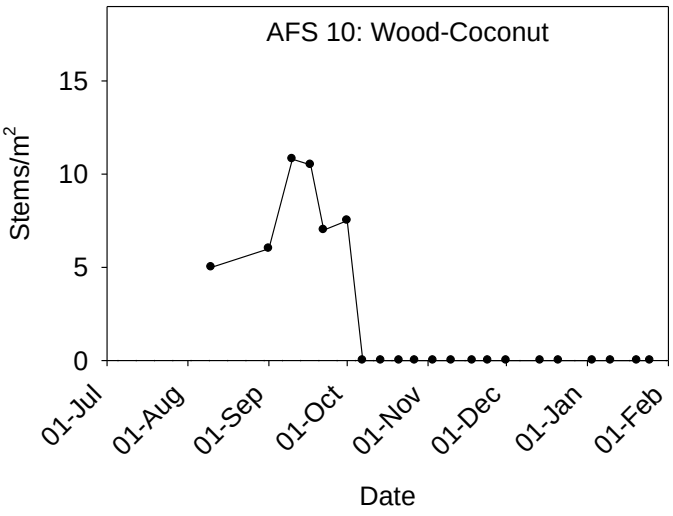
This design is similar to AFS 6 the only difference is that instead of the birch fiber blanket a coconut blanket was used. To increase the buoyancy, two pieces of 1 inch thick Styrofoam (4in.x4ft.)were attached with Nylon cable ties. These structures were buoyant through most of the test period. However, grazers like to rest on the foam. Three structures were removed, because animals broke the cable ties that fasten the floats to the structure.

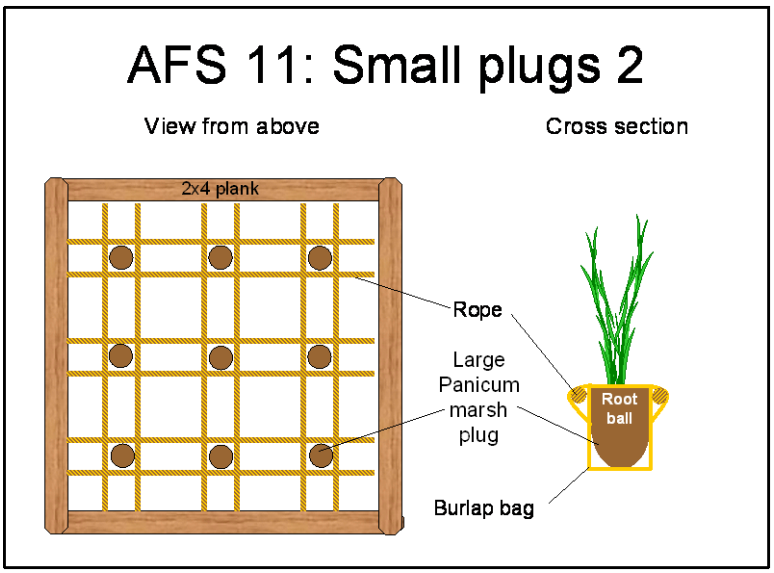




Artificial Floating Structure 10

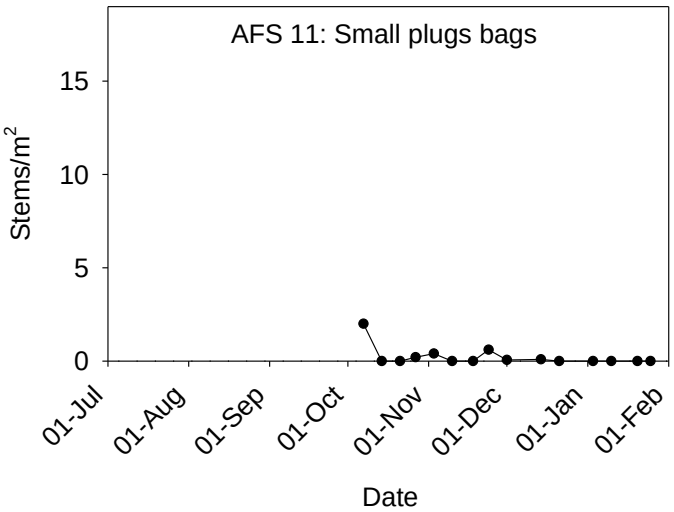
This design is similar to AFS 6 the only difference is that instead of the birch fiber blanket a coconut blanket was used. Four of the five structures sank, therefore all structures were removed from the ponds. A comparison of AFS 10 with AFS 7 and AFS 9 illustrates that the coconut fiber blanket requires a support structure with higher buoyancy than that provided by wood.

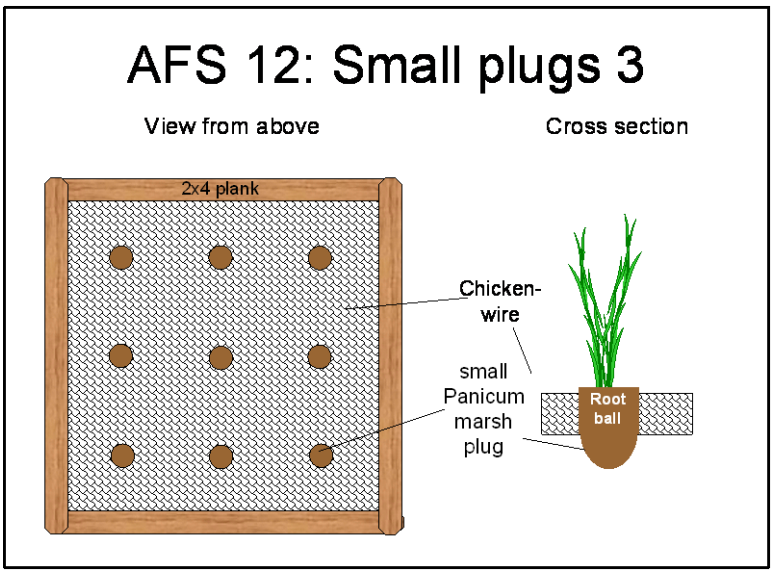




Artificial Floating Structure 11

This design is a miniaturization of AFS 1(4ft x 4ft). All plugs in this design were heavily grazed and no vegetation survived. Four of the structures have been floating at the surface and one sank. Because of deterioration of the burlap material and not being able to protect the structure from aquatic herbivores, these structures were removed in March 2005.





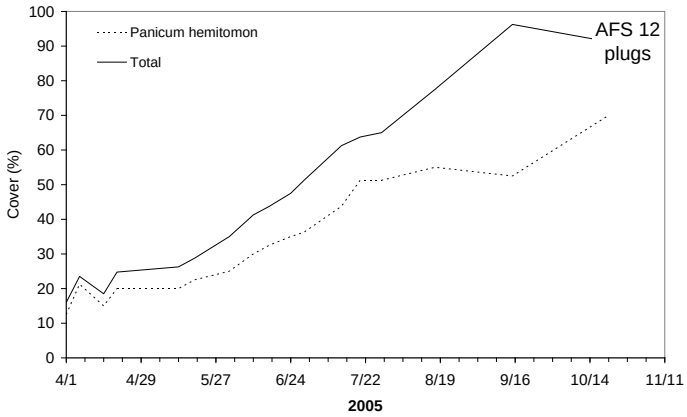
Artificial Floating Structure 12

This design uses a wood frame with a chicken-wire mattress. Nine small plugs marsh vegetation were placed inside these structures(4ft x 4ft).

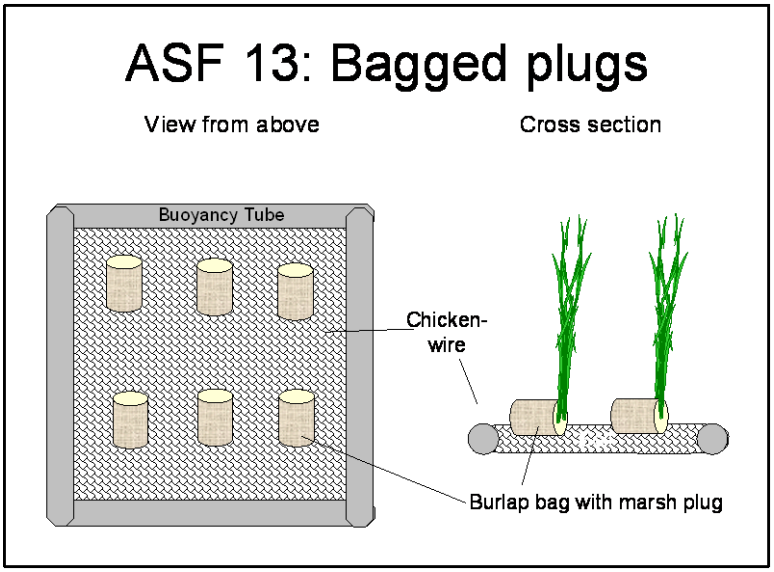
These plugs were heavily grazed immediately following deployment. Structures were fenced in October 2004. However, little recovery of vegetation was observed during the winter. Four of the structures have been floating at the surface and one sank. The four floating structures were replanted with 9 plugs in March 2005. The added plugs remained in good condition through the growing season and *P. hemitomon* cover has increased from 12% on April 1 to 70%. Although other species occurred in these structures, they never out competed *P. hemitomon*.

AFS 12 on March 23, 2005

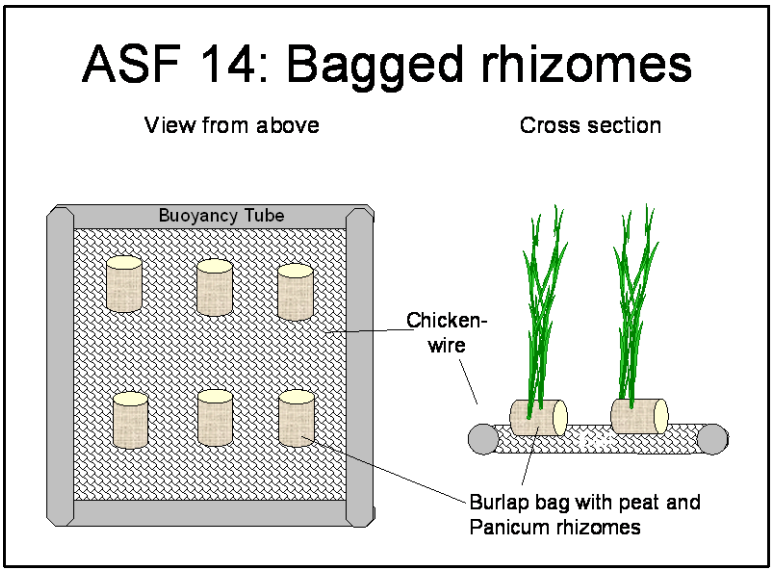
AFS 12 on August 22, 2005



Additional Designs Started in the Spring of 2005



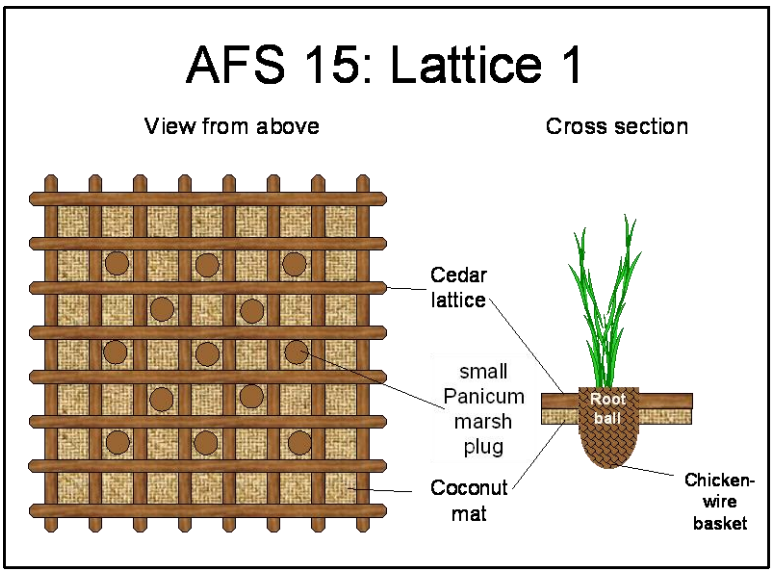
Artificial Floating Structure 13
This design uses a PVC frame (4ft x 4ft x 1in PVC) with a chicken-wire hammock. The frame supports 6 marsh plugs with the root mat enclosed in a small burlap bag. This design is currently unfenced. Average *P. hemitomon* cover was 7.5% on April 1, 2005, and hovered around that value throughout the growing season. Periodically signs of grazing were observed.



Artificial Floating Structure 14
This design uses a PVC frame (4ft x 4ft x 1in PVC) with a chicken-wire hammock. The frame supports 6 small burlap bags filled with a mixture of peat, bagasse, and *P. hemitomon* rhizome fragments. This design is remained unfenced. Due to grazing pressure *P. hemitomon* never became established on these structures, even though they maintained buoyant through the growing season.

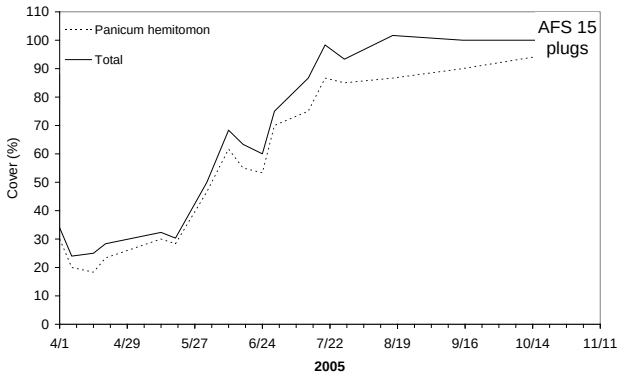
AFS 13 and 14 on June 10, 2005

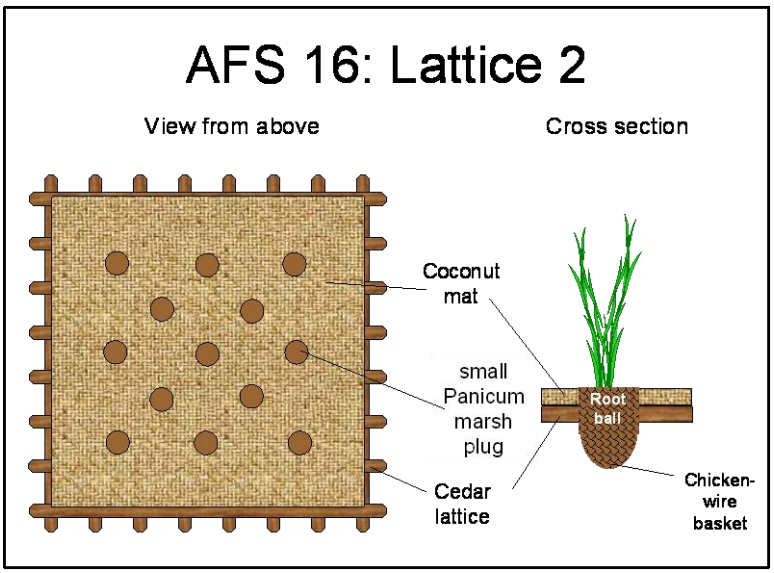
AFS 13 and 14 on August 22, 2005



Artificial Floating Structure 15

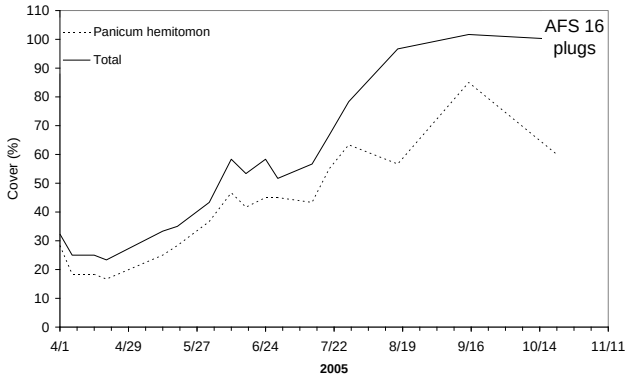
This design uses a lattice of cedar planks(4ft x 4ft x 0.25 inch). Thirteen marsh plugs are suspended in chicken-wire baskets in the lattice openings. To provide a medium for lateral root spread, a coconut blanket is stapled to the bottom of the lattice. This design includes a fence. Bamboo was added to increase buoyancy after these structures submerged in early May. Average *P. hemitomon* cover was 30% on April 1, 2005, and increased to 95% by the end of the 2005 growing season. This increase was despite the submergence of some of the structures.

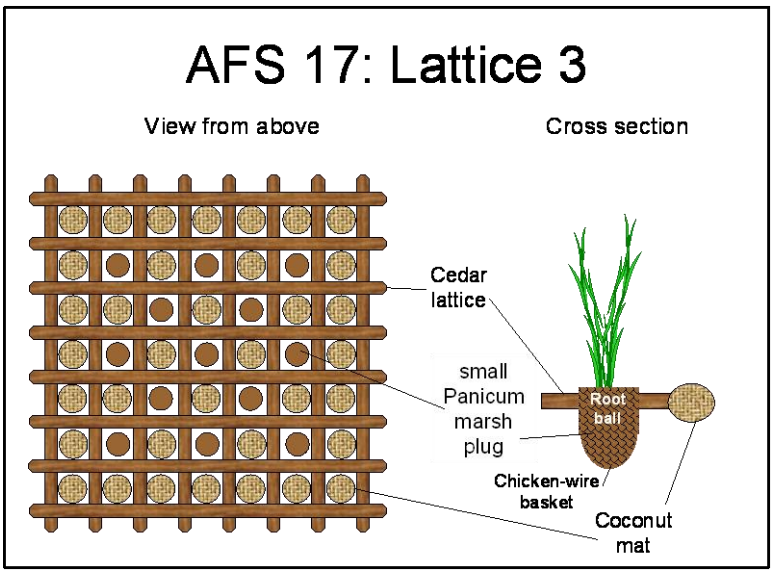




Artificial Floating Structure 16

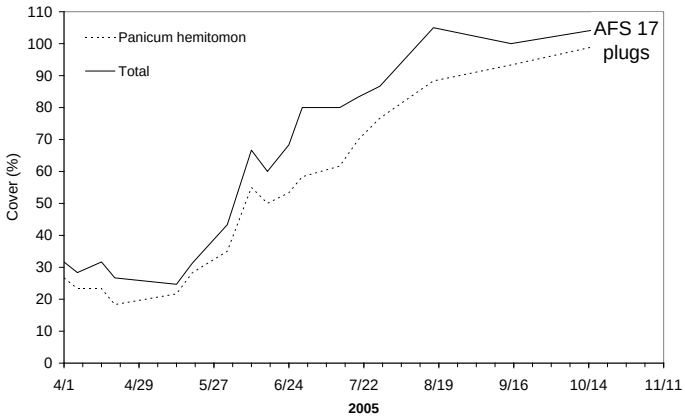
This design uses a lattice (4ft x4ft x 0.25 inch) of cedar planks. Thirteen marsh plugs are suspended in chicken-wire baskets in the lattice openings. To provide a medium for lateral root spread, a coconut blanket is stapled to the top of the lattice. This design includes a fence. Bamboo was added to increase buoyancy after these structures submerged in early May. Average *P. hemitomon* cover was 28% on April 1, 2005, and increased to 75% on September 15, 2005. This increase was despite the submergence of some of the structures in July.

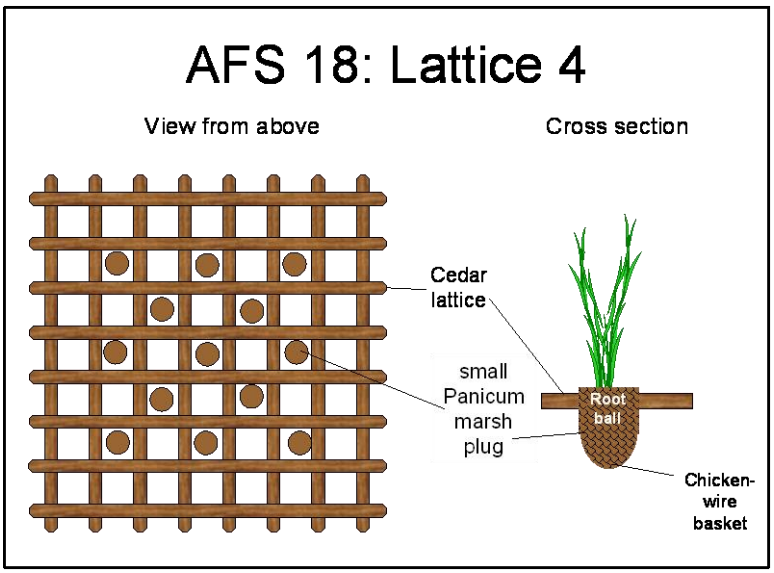




Artificial Floating Structure 17

This design uses a lattice (4ft x 4ft x 0.25 inch) of cedar planks. Thirteen marsh plugs are suspended in chicken-wire baskets in the lattice openings. To provide a medium for lateral root spread pieces of coconut mat are stuffed in the remaining lattice openings. This design includes a fence. Bamboo was added to increase buoyancy after these structures submerged in early May. Average *P. hemitomon* cover was 27% on April 1, 2005, and increased to 100% and the end of the 2005 growing season. All of these structures lost full buoyancy in July. Note: These structures were accidentally labeled as 18 in the field.

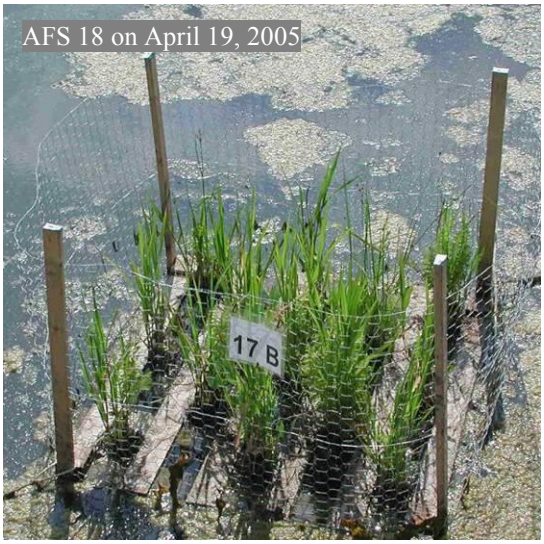


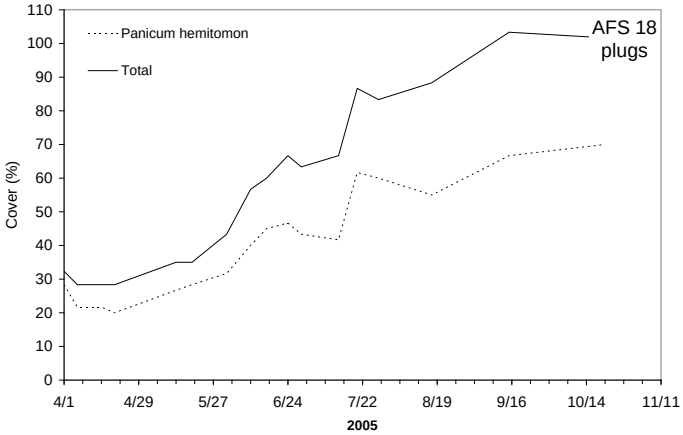


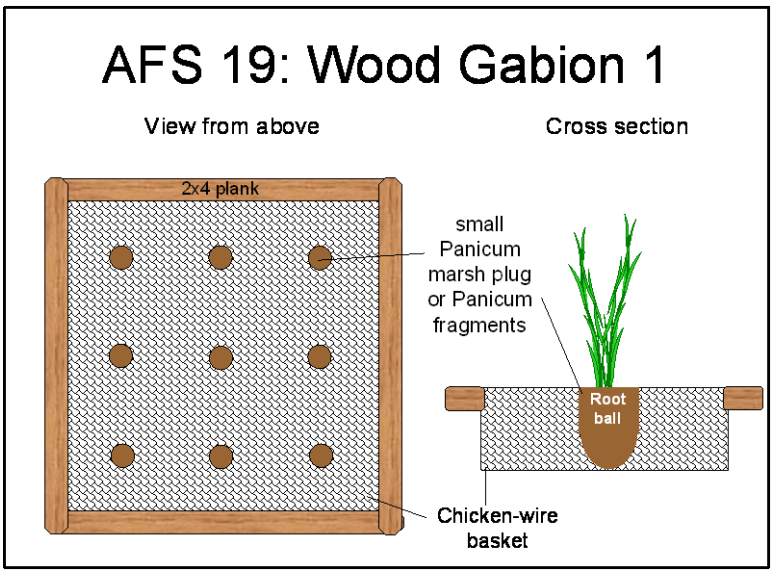
Artificial Floating Structure 18

This design uses a lattice (4ft x 4ft x 0.25 inch) of cedar planks. Thirteen marsh plugs are suspended in chicken-wire baskets in the lattice openings. This design includes a fence. Bamboo was added to increase buoyancy after these structures submerged in early May.

Average *P. hemitomon* cover was 28% on April 1, 2005, and increased to 70% by the end of the 2005 growing season. Several of these structures lost full buoyancy in July. Note: These structures were accidentally labeled as 17 in the field.

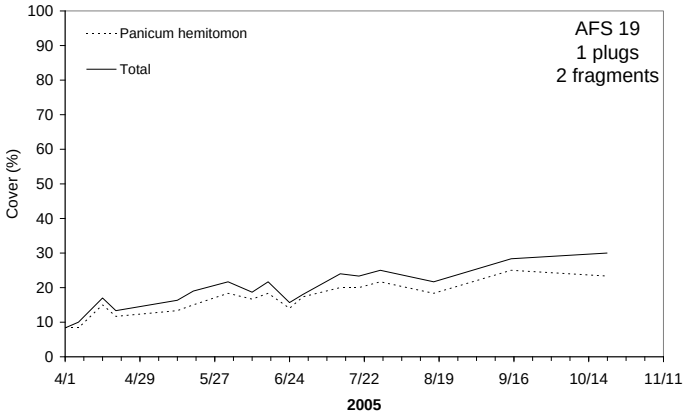


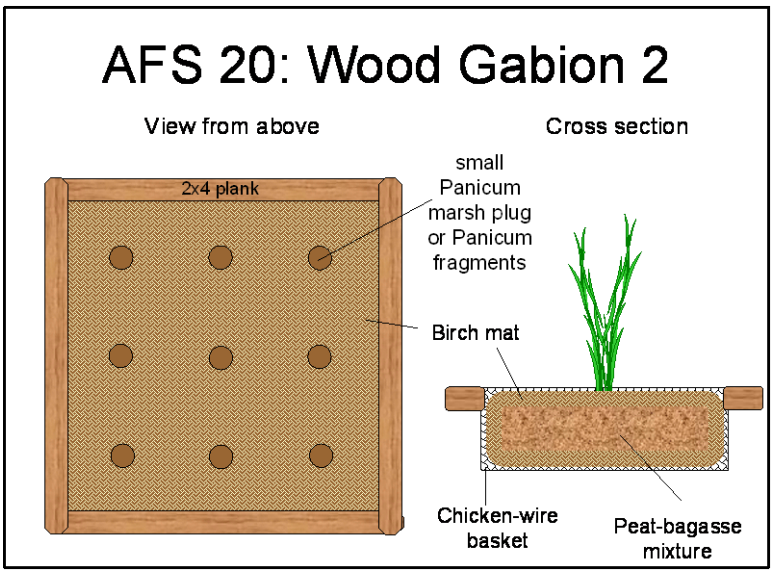




Artificial Floating Structure 19

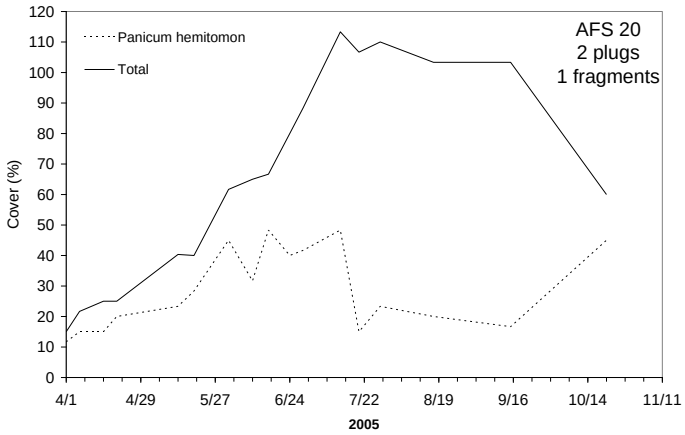
This design uses a wood frame (4ft x 4ft) with a gabion basket. The basket is used to support hydroponic plant growth. This design includes a fence. One of these structures was planted with marsh plugs and the other two were planted with *P. hemitomon* whole plants. This design submerged in mid April and bamboo was added to get the structures to float at the surface. However, submerging of these structures continued through the growing season. Average *P. hemitomon* cover was 8% on April 1, 2005, and increased to a maximum of 25% by September 16, 2005. There was a substantial difference between the plug planted structure and the two fragment planted structures. The fragment planted structures only reached an average cover of 12% while the plug planted structure reached 50% *P. hemitomon* cover.

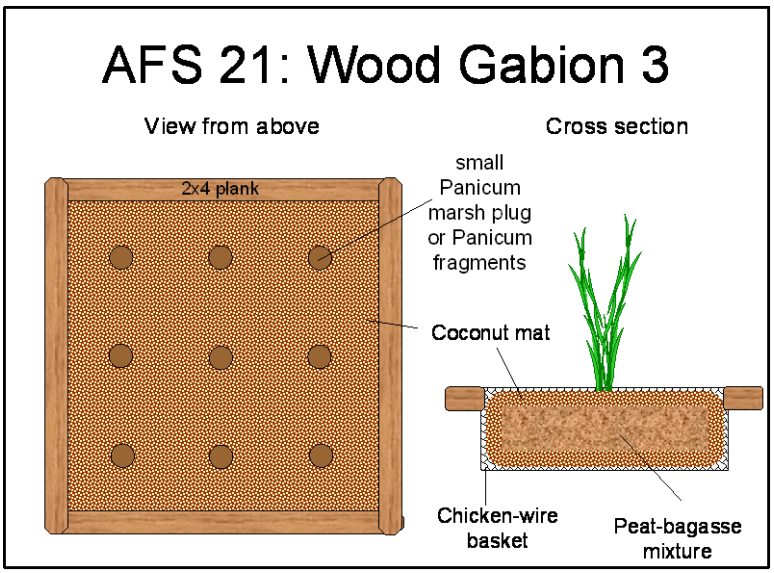




Artificial Floating Structure 20

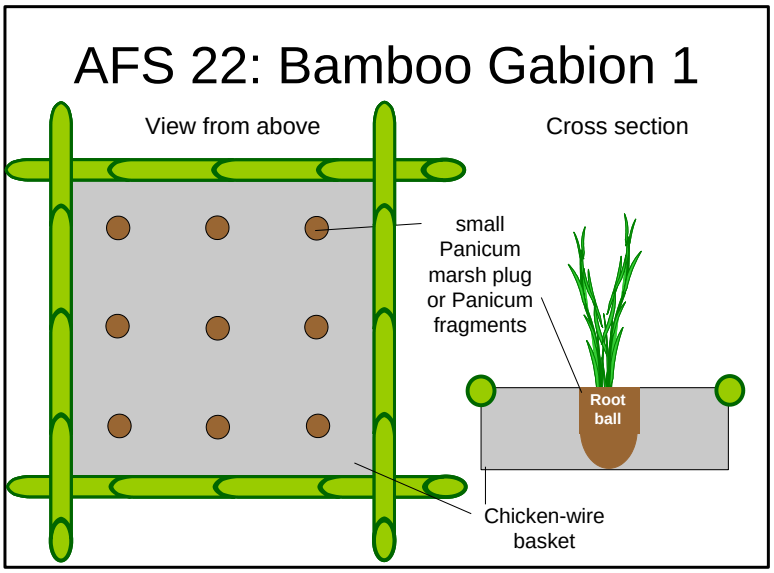
This design uses a wood frame with a gabion basket (4ft x 4ft x 0.5 inch). The basket is filled with a birch mat topped by a peat and bagasse mixture topped by another birch mattress. Two structures were planted with marsh plugs and one structure with *P. hemitomon* whole plants. This design includes a fence. Bamboo was added to this design in March to provide sufficient buoyancy. Average *P. hemitomon* cover was 12% on April 1, 2005, and increased to 48% by July 13, 2005. Growth of *Ludwigia* sp. in these structures was rapid and began overtopping *P. hemitomon* in July. The weight and uneven distribution of *Ludwigia* also contributed to the submergence of these structures in July and the overturning of one of these structures during Hurricane Katrina.





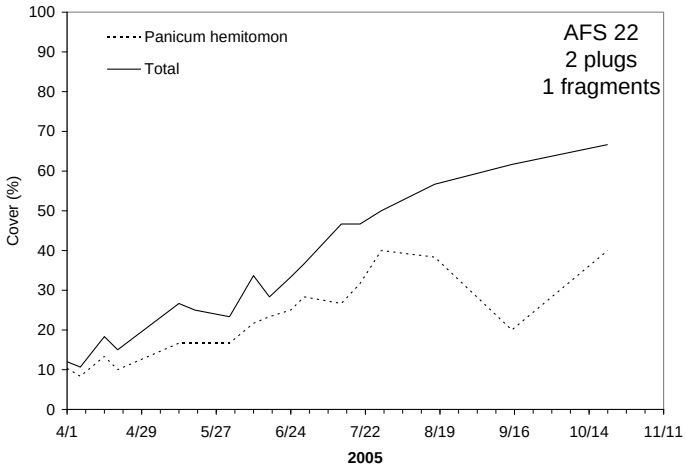
Artificial Floating Structure 21

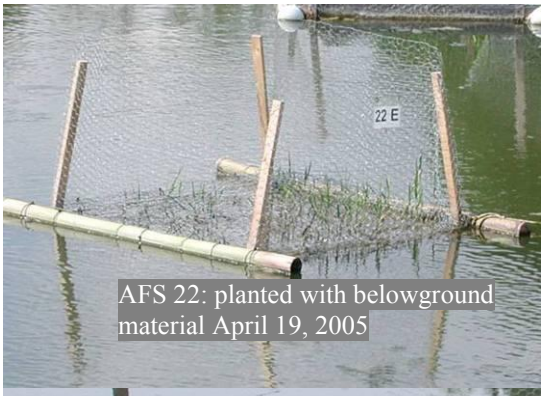
This design uses a wood frame with a gabion basket(4ft x 4ft x 0.5 inch). The basket is filled with a coconut mat topped by a peat and bagasse mixture topped by another coconut mattress. Two structures were planted with marsh plugs and one structure with *P. hemitomon* whole plants. This design includes a fence. Bamboo was added to this design in March to provide sufficient buoyancy. Average *P. hemitomon* cover was 10% on April 1, 2005, and increased to 42% by June 1, 2005. In July, *P. hemitomon* cover slowly decreased due to competition with *Ludwigia* sp. The weight and uneven distribution of *Ludwigia* also contributed to the submergence of these structures in July.



Artificial Floating Structure 22

This design uses a bamboo frame with a gabion basket (4ft x 4ft). The basket supports hydroponic plant growth. This design includes a fence. Average *P. hemitomon* cover was 10% on April 1, 2005 for those structures planted with marsh plugs or whole plants in March. *P. hemitomon* reached the highest cover of 40% at the end of July. Other species mainly sedges added additional cover later in the growing season.

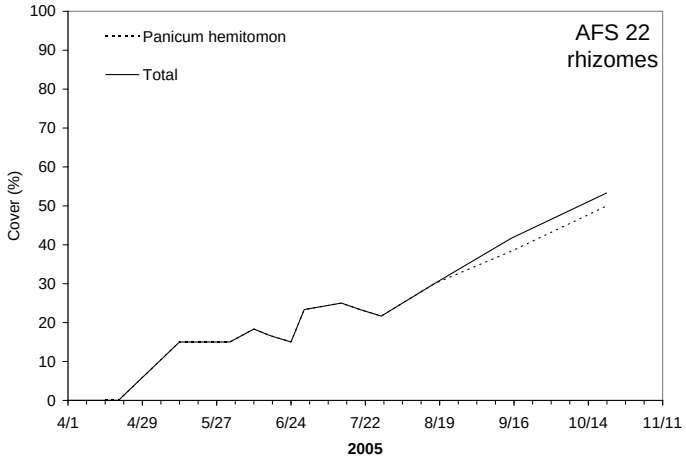




AFS 22: planted with belowground material April 19, 2005

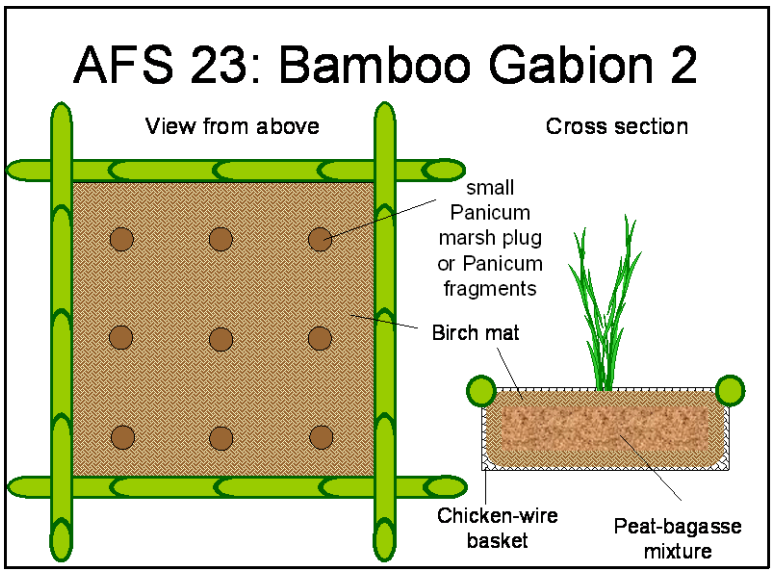
AFS 22: planted with belowground material August 22, 2005

In mid-April, there were 3 replicates added planted with aboveground material only and 3 replicates with belowground material only. The belowground material sprouted within 5 days and had an average cover of 2%. The *P. hemitomon* cover kept increasing in these structures and reached 40% at the end of the growing season.



In contrast, none of the structures planted with aboveground material showed sprouting within the first 5 days. Although a few sprouts appeared, growth in the aboveground material planted structures was very limited.

AFS 22: planted with aboveground material August 22, 2005

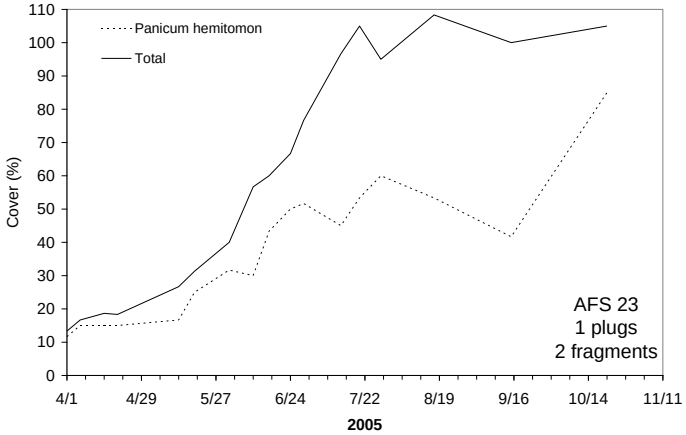


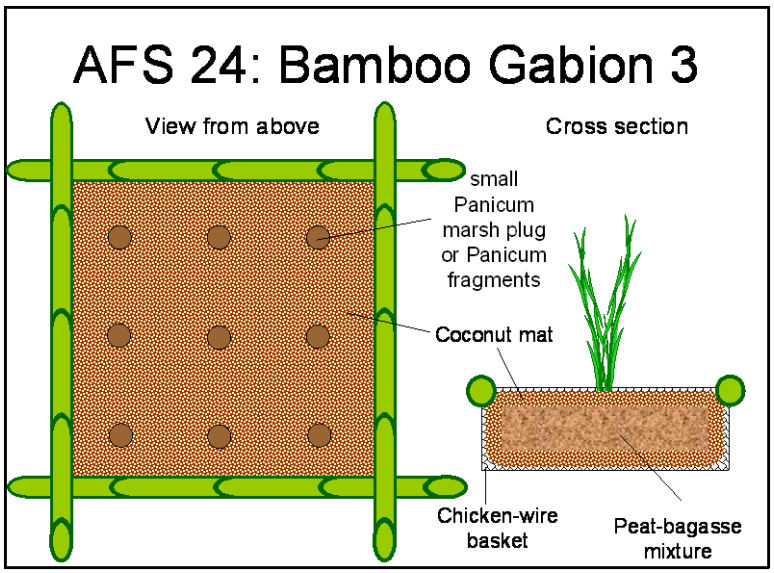
Artificial Floating Structure 23

This design uses a bamboo frame with a gabion basket(4ft x 4ft). The basket is filled with a birch mat topped by a peat and bagasse mixture topped by another birch mattress. This design includes a fence. Average *P. hemitomon* cover was 12% on April 1, 2005, this increased to 85% at the end of the growing season. Although *Ludwigia* sp. appeared in the plug planted structure, no significant submergence occurred until very late in the growing season.

AFS 23 planted with whole plant material
April 19, 2005

AFS 23 planted with whole plant material
August 22, 2005



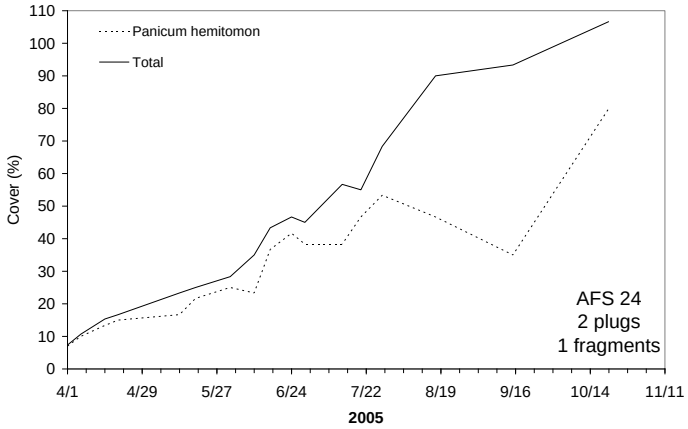


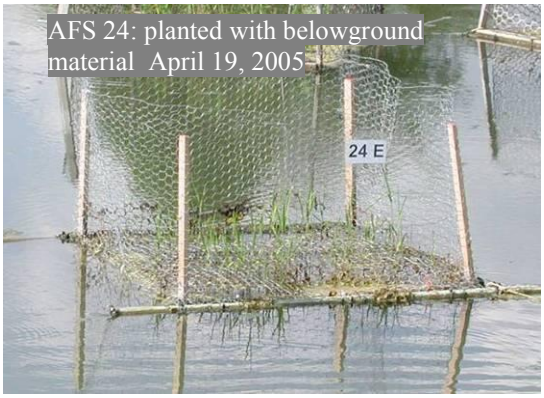
Artificial Floating Structure 24

This design uses a bamboo frame with a gabion basket(4ft x 4ft). The basket is filled with a coconut mat topped by a peat and bagasse mixture topped by another coconut mattress. This design includes a fence. Average *P. hemitomon* cover was 15% on April 1, 2005 for those structures planted with marsh plugs or plant whole plants in March. By the end of the growing season *P. hemitomon* cover had increased to 80%.

AFS 24 planted with whole plant material
April 19, 2005

AFS 24 planted with whole plant material
August 22, 2005



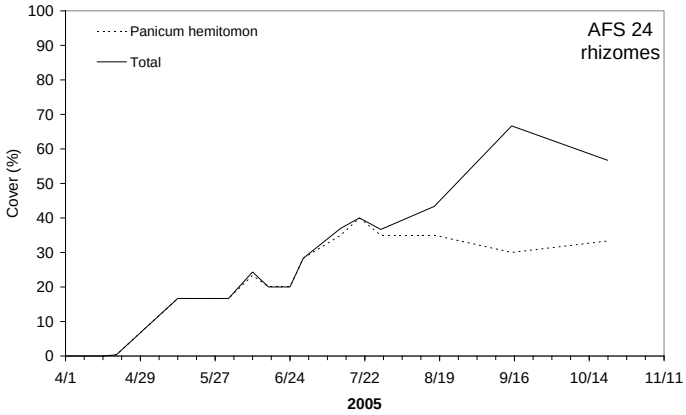


AFS 24: planted with belowground material April 19, 2005

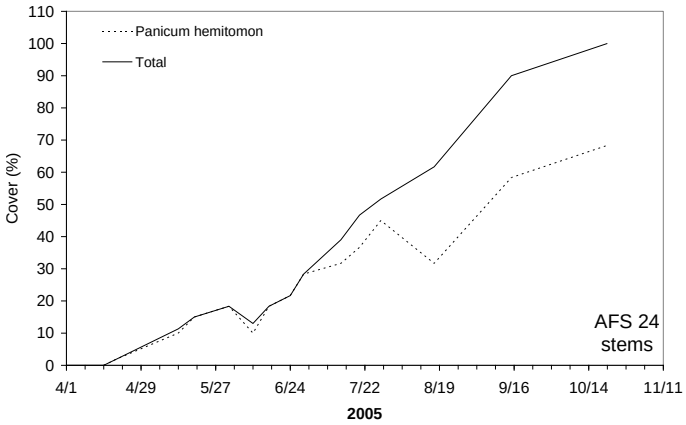
AFS 24: planted with belowground material August 22, 2005

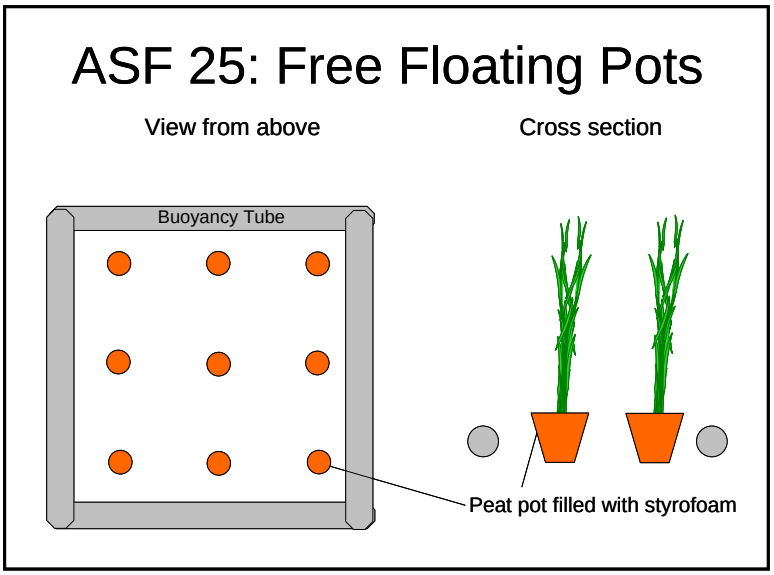
AFS 24: planted with stems August 22, 2005

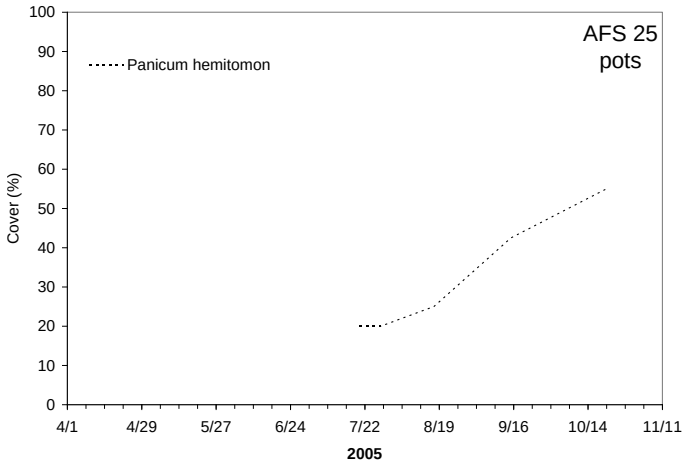
In mid-April, there were 3 replicates added planted with aboveground material and 3 replicates with belowground material. The belowground material sprouted within 5 days and had an average cover of 2%. *P. hemitomon* cover in creased to a maximum of 40% in mid-July, when *P. hemitomon* cover stabilized and other species such as *Leersia oryzoides* and *Scirpus cubensis increased in cover*.



Only one of the structures planted with aboveground materials showed sprouting within the first 5 days. However within the next week all structures had sprouts and *P. hemitomon* cover soon was larger in the stem planted structures than in the belowground material planted structures. End-of-growing season cover for *P. hemitomon* was 68%.

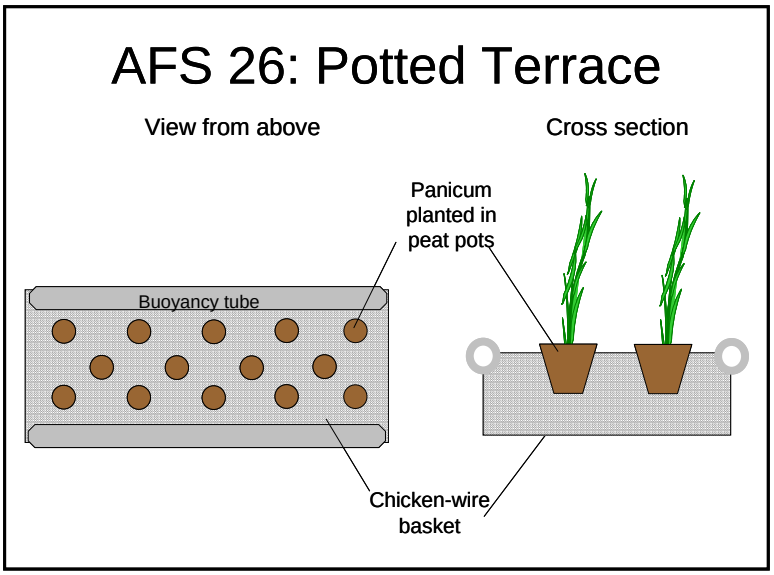






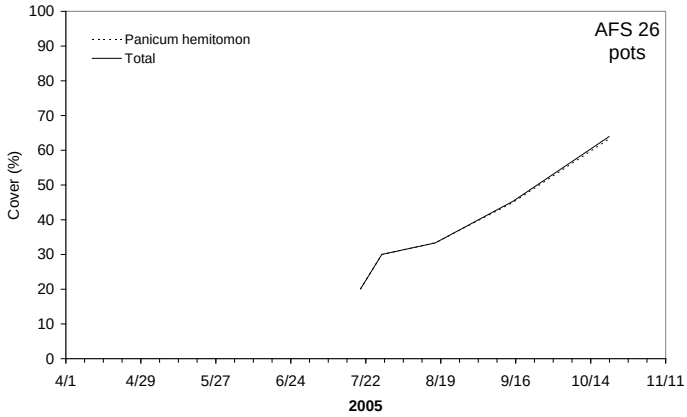
Artificial Floating Structure 25

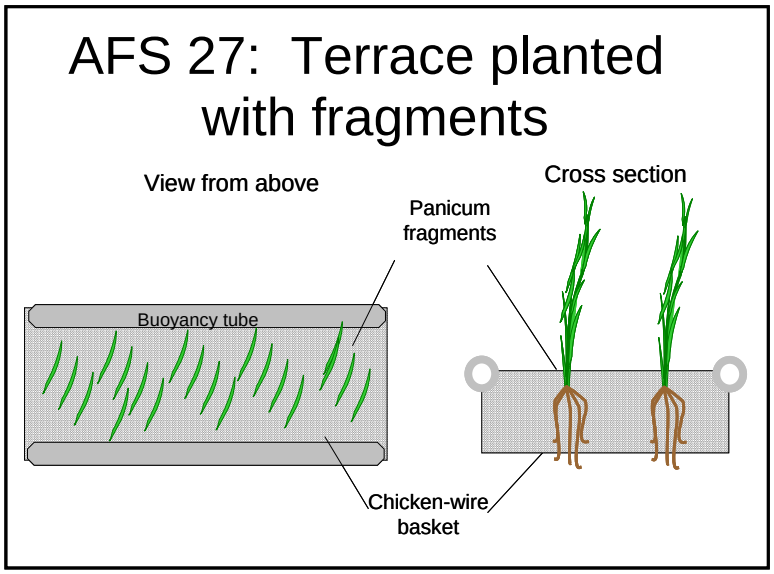
This design uses a PVC frame that contains free floating peat pots filled with styrofoam(4ft x 4ft x 3in PVC). The purpose of the PVC frame is to keep the pots corralled and to support a fence. These structures were deployed in late July 2005, with an average *P. hemitomon* cover of 20%. By the end of the growing season *P. hemitomon* cover had increased to 55%.

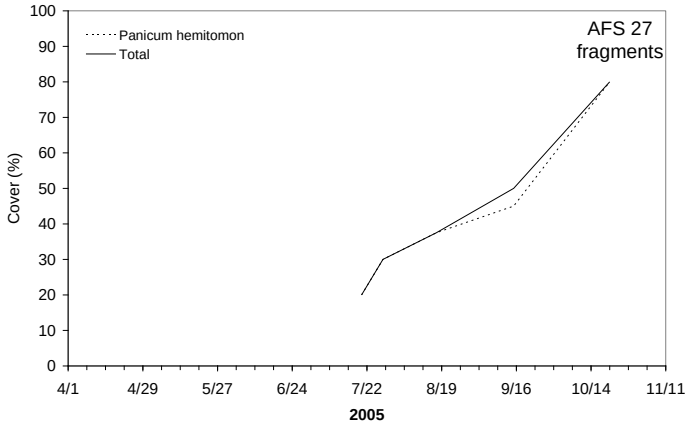


Artificial Floating Structure 26

This design uses a PVC frame that supports a chicken-wire basket(4ft x 10ft x 3in PVC). Peat pots planted with *P. hemitomon* are placed in slits in the top of the wire basket. This design includes a fence. These structures were deployed in late July 2005, with an average *P. hemitomon* cover of 20%. By the end of the growing season *P. hemitomon* cover had increased to 63%.





Artificial Floating Structure 27

This design uses a PVC frame that supports a chicken-wire basket(4ft x 10ft x 3in PVC). Whole plant pieces of *P. hemitomon* are placed in slits in the top of the wire basket. This design includes a fence. These structures were deployed in late July 2005, within a week the average *P. hemitomon* cover reached 20%. By the end of the growing season *P. hemitomon* cover had increased to 80%.