ALTERNATIVE NITROGEN FERTILIZER MANAGEMENT STRATEGIES TO IMPROVE FERTILIZER RECOVERY AND WATER QUALITY IN WETLAND TARO (*COLOCASSIA ESCULENTA*) PRODUCTION SYSTEMS

FINAL REPORT

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Contents

Executive Summary

Commercial wetland taro production requires nitrogen (N) fertilization to maintain corm yields and profitability. Current N fertilization practice on most commercial taro farms consists of monthly applications of urea directly into the surface water of the ponded fields. Due to fertilizer inefficiencies and potential downstream N contamination of fragile freshwater and marine ecosystems, a CTAHR funded project was implemented in Hanalei to evaluate the effect of a controlled release urea and organic fertilizer on taro yield, N use efficiency and water quality.

A controlled experiment with four treatments including a check plot (no fertilizer), fish bone meal organic fertilizer (FBM), Duration® (polymer coated urea) fertilizer, and a farmer practice using conventional urea fertilizer was established at four commercial farms in Hanalei Valley. Fertilizer treatment effects on water and soil N concentration was assessed through water and soil sampling. Analysis of variance was used to evaluate treatment effects on taro yield, fertilizer N use efficiency, and economic return to the farmer.

Fertilizer treatment had no significant effect on mean taro yield. The polymer coated urea (PCU) controlled release fertilizer showed the highest average yield and lowest amount of variation. The fish bone meal (FBM) and PCU fertilizers provided a long term reservoir of plant available N in the root zone, and reduced N export to the river system in effluent water. The current farmer practice did not store applied N in the soil, but rather showed an increased export of N to the river system with potential to contaminate fragile downstream freshwater and marine ecosystems. Varying fertilizer did not improve N use efficiency. Results from a partial cost benefit analysis showed that the PCU fertilizer treatment showed the highest mean return with the lowest variability across the three farm sites.

Results from the experiment indicate that the Duration® PCU product from Agrium Technologies is an economically viable alternative to conventional urea with the added benefit that it will reduce potential N contamination of fragile downstream aquatic resources. Further on-farm tests are recommended to confirm that net returns are higher or similar to conventional fertilization over time.

Background and Purpose

Wetland taro is grown in Hawaii to produce poi taro, a staple food prized by native Hawaiians and local consumers alike. Commercial production of taro for poi milling requires N fertilizer applications to maintain corm yields. Conventional taro farms currently apply N fertilizers, typically as urea (46-0-0), directly into the floodwaters at monthly intervals for the first six months of the crop. Much of the urea N applications to the surface water may not be taken up by taro plants because N is subject to a number of loss pathways. As urea hydrolyzes in the floodwaters ammonium (NH_4^+) is released, which can be rapidly nitrified in the oxic water to nitrate (NO_3^-). Both NH_4^+ and NO_3^- forms of N can leave taro fields in the floodwater, enter freshwater streams or rivers, and ultimately move into coastal waters posing an environmental threat to fragile coastal and marine ecosystems. Additionally, N can be lost to the atmosphere when NH_4^+ volatilizes to ammonia (NH_3) gas during diurnal increases in surface water pH. Lastly, when the NO_3^- from the nitrified urea diffuses into the anoxic subsoil it is converted to N_2O through denitrification and lost to the atmosphere.

In order to address the inefficiencies associated with current N Management, CTAHR funded a project to evaluate the use of controlled-release urea and organic fertilizers as alternative fertilization strategies in wetland taro production. The project addressed two specific objectives: 1) to assess the effect of polymer coated urea (PCU) and fish blood meal (FBM) on taro yields and N recovery in wetland taro, and 2) to determine the effect of slow release N and organic fertilizers on N in the water and soil. The alternative fertilization strategies were hypothesized to keep applied N in the NH_4^+-N form in the soil sediment to make it available for taro plant uptake with the following benefits: 1) increase N recovery, 2) decrease loading of N into the Hanalei River, and 3) increase taro yield.

Approach and Experimental Design

Experimental Design

Four farmers with the Kauai Taro Growers Association agreed to participate and donate one taro field to be used in the experiment. The four fields were located within the Hanalei Wildlife Refuge (Fig. 1) and situated on the Hanalei soil series (*very fine, mixed, semiactive, nonacid, isohyperthermic Typic Endoaquepts*). Soil samples were collected from each field and analyzed at the Agricultural Diagnostic Service Center (ADSC) at the University of Hawaii to determine baseline fertility status. Sampling results are presented in Table 1. The field selected at Farm 2 had been fallow for at least 10 years, and showed significantly different soil fertility status compared to the three other taro fields, which had been under continuous taro cultivation for decades.

Table 1. Baseline soil sample results for lo`i from the four participating farms.

Farm ID	pH	TC	TN	P	K	Ca	Mg
		-----------%----------		------------------------ppm---------------------			
1 (RH)	6.0	1.8	0.12	168	179	2248	910
2 (AD)	5.2	5.5	0.29	13	91	1126	1124
3 (MF)	6.2	2.4	0.08	105	155	2569	890
4 (GK)	6.0	2.8	0.19	160	130	1945	1001

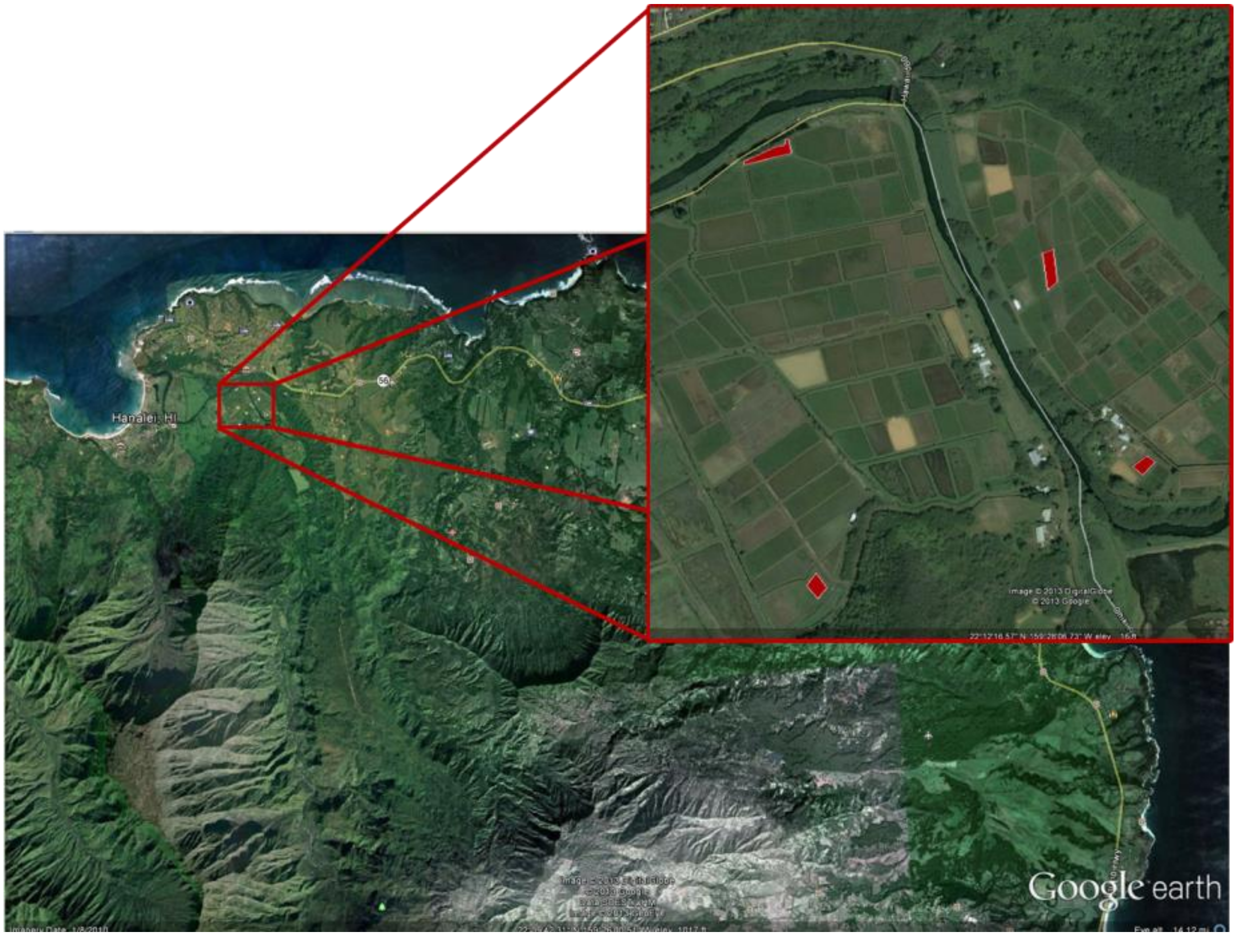

Figure 1. North Shore of Kauai with inset showing locations of the four lo`i (red polygons) within the Hanalei Wildlife Refuge.

Each field was subdivided into four distinct plots using plywood barriers inserted into the sediment with a pipe system to allow for individual entry and exit of irrigation water into each plot (Fig. 2). Four fertilizer treatments, including including T1 check plot (no fertilizer), T2 fish bone meal organic fertilizer (FBM), T3 Duration® (polymer coated urea, PCU), and T4 farmer

Figure 2. Construction activities associated with the implementation of experimental plots at select Hanalei taro farms.

control urea were randomly assigned one plot at each farm. All fields received a basal application of K as 0-0-50 at equivalent rate of 600 lbs per acre. Lime and fertilizers were tilled into the fields prior to installation of barriers. All plots were planted with the same taro variety (Maoli Lehua) between February 15 and February 23, 2011. Planting density was equivalent to 10,890 plants per acre across all farms. The check plots received no fertilizer inputs for the duration of the experiment. The fish bonemeal organic fertilizer obtained from Island Commodities, Inc. of Kapolei, Oahu contained rendered fish and slaughterhouse scraps with the following analysis: N = 7.67%, P = 2.81%, K = 0.86%, Ca = 4.50%, Mg = 0.16%. The Duration fertilizer (43-0-0) utilized in T3, a polymer coated controlled release urea product (PCU), was obtained from Agrium Advanced Technologies (Denver, CO) and formulated to meet the following specifications: 25% (w/w) 45 day release, 50% (w/w) 90 day release, 25% (w/w) 180 day release. The farmer control treatment (T4) consisted of monthly applications of urea (46-0-0) applied directly into the ponded plots. Lime was applied at the equivalent of 2,000 lbs per acre and P fertilizer as triple super phosphate (0-45-0) at the equivalent of 200 lbs per acre at farm 2 to correct soil acidity, low Ca and low P concentrations. All N fertilizers were applied to achieve a rate of 480 lbs N per acre and the specific amounts applied to each plot are outlined in Table 2. Fertilizer materials for T2 and T3 were tilled into the flooded plots on February 8 and 9, 2011

Table 2. Plot size at each farm and corresponding amount of fertilizer applied.

Farm	Treatment	Plot Area (ft^2)	Fertilizer Application
1	T4	9,085	36.3 lbs 46-0-0/mo
	T3	1,520	38.7 lbs
	T2	1,680	301 lbs
2	T4	2,376	9.5 lbs 46-0-0/mo
	T3	1,840	46.8 lbs
	T2	1,800	323 lbs
3	T4	10,500	41.9 lbs 46-0-0/mo
	T3	1,400	35.6 lbs
	T2	1,360	244 lbs
4	T4	4,320	17.2 lbs 46-0-0/mo
	T3	1,500	38.2 lbs

T2	1,600	287 lbs

Figure 3. Application of fish bone meal fertilizer (left) and tillage operation to incorporate fertilizer materials.

(Fig. 3), and plot outlets were closed for two weeks to prevent the loss of water from the plots.

Soil and Water Sampling

Soil and water sampling commenced on March 7, 2011. Soil samples were collected monthly to a depth of six inches using a plastic coring tube with a 2.5 inch diameter. Six cores were taken from each plot, homogenized and a sub-sample placed in a ziplock bag and stored on ice immediately after collection. Soil samples were transported in a cooler to the University of Hawaii, MNanoa (UHM) where they were refrigerated, extracted with 2 M KCl within 24 hours, and extracts kept frozen until analyses.

Water samples were collected from the intake point and at each plot exit at all four farms every two weeks until June 27, 2011, and then monthly until harvest. The water quality parameters analyzed on site included temperature, conductivity, total dissolved solids, salinity, dissolved O_2, and pH. These were recorded *in situ* using a YSI portable 556MPS mulitparameter probe (YSI Incorporated, Yellow Springs, OH). A sub-sample from each plot was collected in a 250 mL Nalgene sample bottle, stored on ice, and transported to the University of Hawaii where all samples were filtered through Whatman 42 filter paper and then frozen.

Soil extracts and water samples were then sent by air shipment to the Marine Sciences Analytical Laboratory MSAL) at the University of Hawaii Hilo. The samples were analyzed for nitrate (NO_3^--N) and ammonium (NH_4^+-N) colorimetrically on an autoanalyzer by cadmium reduction and the indophenol blue method, respectively. Water samples were analyzed for total dissolved N using a Shimadzu TNM-1 instrument by high temperature combustion chemiluminesecence detection.

Tissue Analysis

On June 15, 2011, four leaf samples were collected from each plot, brought to the University of Hawaii, dried at 70°C to a constant weight, and analyzed for total elemental concentration at the ADSC.

Taro Harvest and Nitrogen Recovery

Experimental plots were harvested on March 27th and 28th, 2012 to evaluate N fertilizer effect on taro yield, taro density, and N uptake. The two center rows with a length 40 feet from each plot were selected as harvest rows (area = 160 ft^2). Ohana within the harvest area were counted, excavated, roots removed, and keiki and makua separated. Keiki and makua weights were recorded for each plot. Five ohana were randomly selected and flagged in adjacent rows, removed and packed for shipping. These five plants were carried back to UHM, dried at 70°C to a constant weight, dry weight recorded, and analyzed for total elemental concentration at the ADSC. Nitrogen uptake was calculated by multiplying dry weight by tissue N concentration and scaled up to lbs per acre. Apparent N recovery (ANR) was calculated according to the following equation:

$$ANR\ (\%) = \frac{\left(Nuptake_{fertilized} - Nuptake_{check}\right)}{Napplied} \times 100\%$$

Where $Nuptake_{fertilized}$ is the N in the taro plants from the fertilized plots and $Nuptake_{check}$ is the N in the taro plants from the check plots that received no N fertilizer (units are expressed as lbs N per acre).

Statistical Analysis

A one-way analysis of variance (ANOVA) with farm as replicate was used to examine the effect of each fertilizer treatment on taro tissue N concentration (%), yield (lbs taro per acre), and ANR (%). All statistical analyses were performed using the Minitab (16) statistical software package (Minitab, Inc., 2007).

Results

Taro Yield

Use of the same four fertilizer treatments at four separate, but similar taro fields in Hanalei, the farms served replicates of the same experiment and allowed a mean taro yield and a variance to be calculated. This information was used to perform ANOVA and assess the effect of fertilizer treatments on yield. Analysis of variance was performed using yield data from three of the four farms because the taro crop failed at Farm 2. Results of ANOVA showed that N fertilizer type had no significant effect on taro corm yield (Fig. 4a). Mean yields varied from a low of 19,956

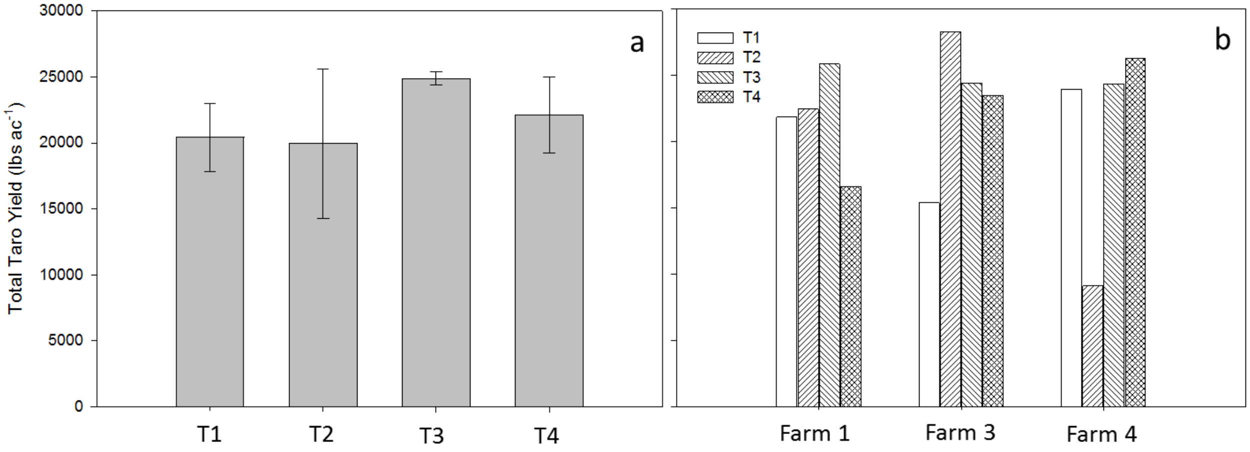

Figure 4. Treatment effect on mean taro yield using each farm as a replicate (a) and treatment effect on taro yield at the individual farms (b).

lbs ac^{-1} in the fish bone meal treatment to a high of 24,888 lbs/ac in the PCU treatment. Considerable variability existed in taro yields (shown by large error bars) in all the treatments except the PCU fertilizer. This indicates that the PCU fertilizer performed consistently across the sites. The FBM fertilizer performed better than urea at Farm 1 and 3, but performed poorly at Farm 4. The urea treatment produced similar taro growth at Farms 3 and 4, but showed relatively low yields at Farm 1. Despite a lack of a significant fertilizer effect, the consistent yield results for the PCU fertilizer material across all three sites is valuable information for taro farmers.

Two notable observations about taro yields can be made as a result of this experiment. The first was the lack of a significant yield response to N fertilization and the second was the overall low yields in the fertilized plots. Contrary to expectations, N fertilization, regardless of the type did not increase yield significantly compared to the 0 N check plots. Figure 4b shows that the 0 N treatment produced a low yield (16,607 lbs ac^{-1}) only at farm 3, and produced yields comparable to the fertilized treatments at farms 1 and 4. At farm 1 the 0 N treatment out-performed the farmer practice treatment and at farm 4 0 N produced better yield than the FBM treatment. The comparable yields of the 0 N treatment at Farms 1 and 4 may be due to the high soil NH_4^+-N in the 0 N plots observed during the first four months of the experiment. Mean soil NH_4^+-N concentration was 53 mg kg^{-1} during the first four months when N demand is highest, which is considered high for a flooded rice system. In flooded taro systems, however, no data that relates soil NH_4^+-N concentration and taro growth exists, but the high NH_4^+-N concentrations could explain the lack of a yield response to added N fertilizers.

In addition to the lack of a significant yield response to N, overall taro yields at the three farms was relatively low compared with expected yields. Typical yields at the participating farms are about 35,000 lbs per acre. Although many factors may have contributed to low taro yields, two possible explanations for our observed yields were: 1) extreme rainfall events in 2011 and 2012, which caused extensive flooding, and 2) extensive *Phytophthora spp.* damage to taro plants during the vegetative growth phase in 2011. Approximately 12 inches of rain fell between May 7 and 9, 2011 causing extensive flooding for several days throughout Hanalei Valley and damaging the experimental plots. In March of 2012, Hanalei Valley experienced another bout of excessive rains between March 4 and 6 and again on March 8. An estimated 50 inches of rain fell between March 3 and 9, which was almost twice the monthly average. The flooding caused by these extreme rainfall events likely contributed to lower than average taro yields. Kona weather patterns in May and June, 2011, when the taro was at the height of vegetative growth, caused an outbreak of *Phytophthora* with significant damage to taro leaves across all treatments at all sites (Fig. 5). *Phytophthora* infestations of taro leaves reduce the photosynthetic capacity of the taro plant and thus cause lower corm yields.

Figure 5. Evidence of heavy phytophora incidence and damage on taro leaves across experimental sites.

<u>*Soil Nitrogen*</u>

Fertilizer treatment effect on soil N status was monitored by measuring $NH_4^+ + NO_3^-$-N throughout the duration of the experiment. Applying urea monthly into the flood water showed small increases in soil NH_4^+-N between 118 and 187 days after planting, but overall soil NH_4^+-N status in the farmer practice (T4) plots were similar to soil NH_4^+-N levels in the 0N (T1) plots (Fig. 6). The PCU fertilizer produced a steep rise in soil NH_4^+-N concentration in two weeks after application with mean concentration at 407 lbs NH_4^+-N per acre and maintained a high NH_4^+-N concentration up to 150 days after application. The organic FBM fertilizer also show a rapid rise in soil NH_4^+-N concentration, which peaked at 309 lbs NH_4^+-N per acre at two months after application and then showed a steady decline beginning at 150 days after application. Soil NH_4^+-N concentrations for the plots receiving monthly urea applications (farmer practice) were generally not different from the 0N control plots except for slightly elevated levels at 118, 145, and 187 days after planting. By 265 days after application all treatments showed NH_4^+-N concentrations similar to the 0N control plot.

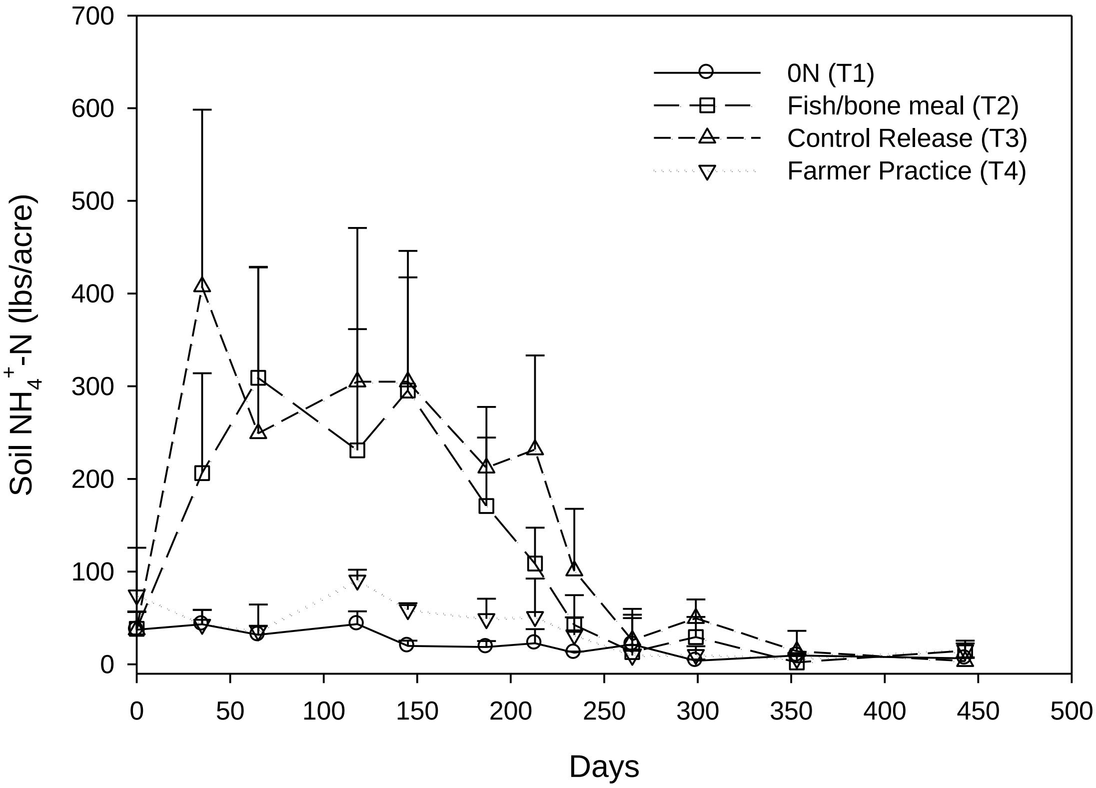

Figure 6. Mean soil NH_4^+-N concentrations for the different treatments. Error bars represent the standard deviation.

Soil NH_4^+-N concentrations in the FBM and PCU fertilizer plots were characterized by high variability. Ammonium release from the FBM fertilizer reached a maximum at 65 days at Farm 3 and 4, but declined more rapidly at Farm 3 (Fig 7A). At Farm 1 the maximum was reached after 118 days. All of the applied N from the PCU fertilizer was recovered as NH_4^+-N at the first sampling date 35 days after application at Farms 1 and 3 (Fig. 7B). Maximum soil NH_4^+-N levels at Farm 4 were not reached until 118 days after application. The NH_4^+-N release pattern observed at Farm 4 was more in line with expectations for a controlled release material. The rapid release of NH_4^+-N observed at Farms 1 and 3 indicated that the material was not conforming to a slow release pattern, but rather releasing all its soluble N within the first 35 days. A 35-day incubation experiment in the laboratory conducted to assess N release from urea and the PCU fertilizers, found that the PCU fertilizer released approximately 46% of the added N as NH_4^+-N compared to 97% in 35 days for the standard urea fertilizer. The PCU fertilizer was formulated to release 25% of the added N within the first 30 days, but appears to be solubilizing N almost twice as fast as the formulation analysis predicts under fully saturated conditions. Overall, however, the FBM and PCU fertilizers provided a large reservoir of plant available N in the soil for up to 200 days of the taro growth cycle whereas the farmer practice fertilization treatment showed little potential to store N in the soil.

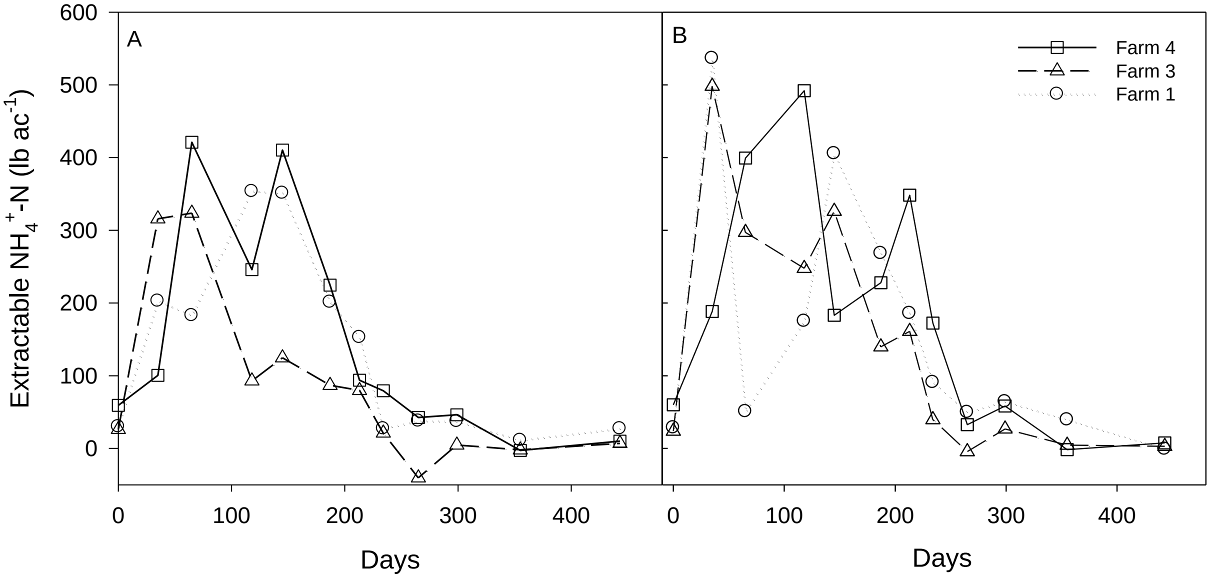

Figure 7. Soil NH_4^+-N concentrations for the plots amended with fish bone meal (A) and controlled release urea fertilizer (B) at Farms 1, 3, and 4.

Water Nitrogen

Total N (NH_4^+-N, NO_3^--N, + organic N) concentrations in the outflow water for each treatment at the three farms are displayed in Figure 8. The 0N plots (T1) showed low total N in the water at all sites throughout the sampling period. The FBM and PCU fertilizer treatments showed elevated total N in the outflowing water during the first two sampling events at Farms 1 and 3 and up to the fourth sampling event (8 weeks) at Farm 4. Urea fertilization events produced pronounced spikes in water N concentration at Farms 1 and 4, but the relationship between fertilization event and water N concentration was less apparent at Farm 3. The relationship between urea fertilization and water N spikes was clearest at Farm 4. The effect of N fertilization on potential for N loading into the Hanalei river system was evaluated by comparing effluent water N concentration with the accepted limit that background total N concentration in natural water bodies is less than 1.0 mg L^{-1} (US Geological Survey, 1999). Total N concentration in water from Hanalei River flowing into the patches (inflow), exceeded 1.0 mg L^{-1} only once at Farm 4 for the duration of the experiment (Fig. 9). For the check plots not receiving any N fertilizer, N concentrations surpassed the limit three times at Farm 1 and once at Farm 4. Water samples collected at Farm 3 generally showed little effect of N fertilization on water N concentration with the farmer practice treatment and PCU treatments showing elevated N concentration for 2 out of the 14 sampling events. The FBM treatment exceeded 1.0 mg L^{-1} three times. At Farms 1 and 4 the N fertilizer treatment had a much more significant effect on N water concentrations. At Farm 1, the FBM fertilizer caused N water concentrations to exceed the limit in 50% of the samples (7/14) and more than half the samples for the PCU fertilizer (8/14). Similarly, the FBM and PCU fertilizers resulted in elevated N concentrations in 5 and 6

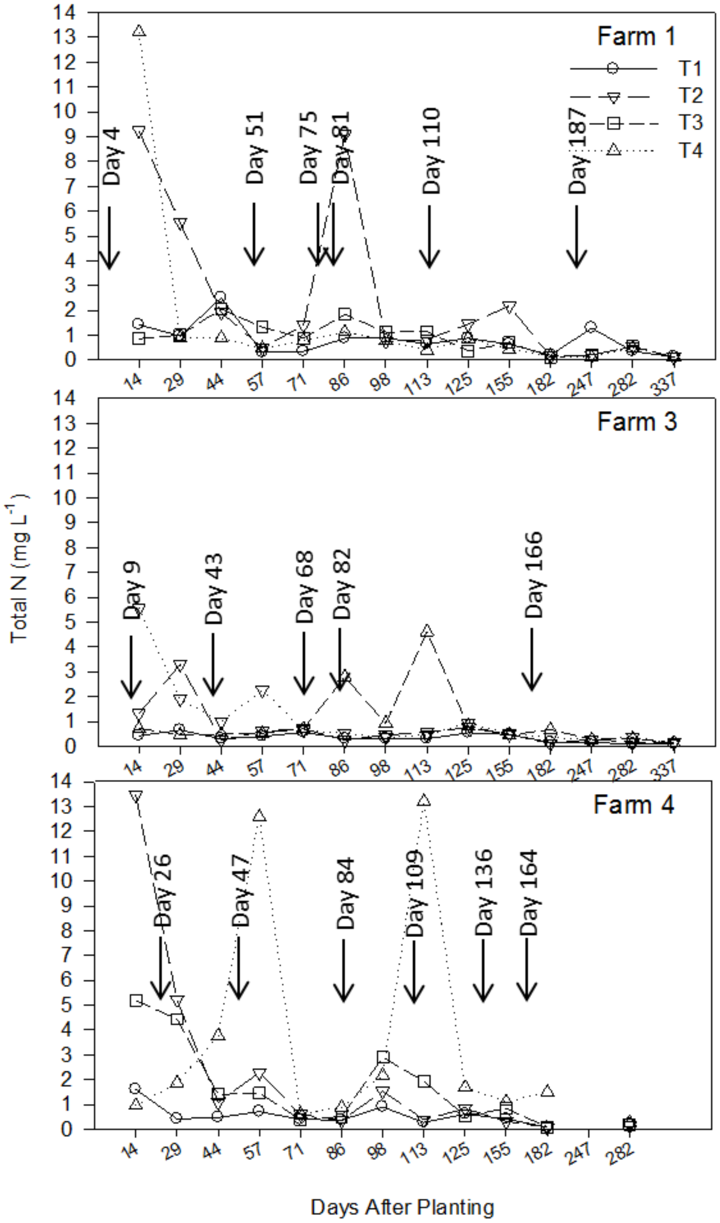

Figure 8. Total N concentration in water samples collected from outflow pipes for each treatment. Urea fertilization events for Farmer Practice treatments (T4) are indicated with arrows.

elevated N concentrations in 5 and 6 of the 14 sampling events, respectively. Results for the farmer practice treatment were not consistent at Farms 1 and 4 with a high incidence of excess N in the water at Farm 4 (8/14), but low incidence at Farm 1 (1/14). The inconsistencies were difficult to explain with the current data.

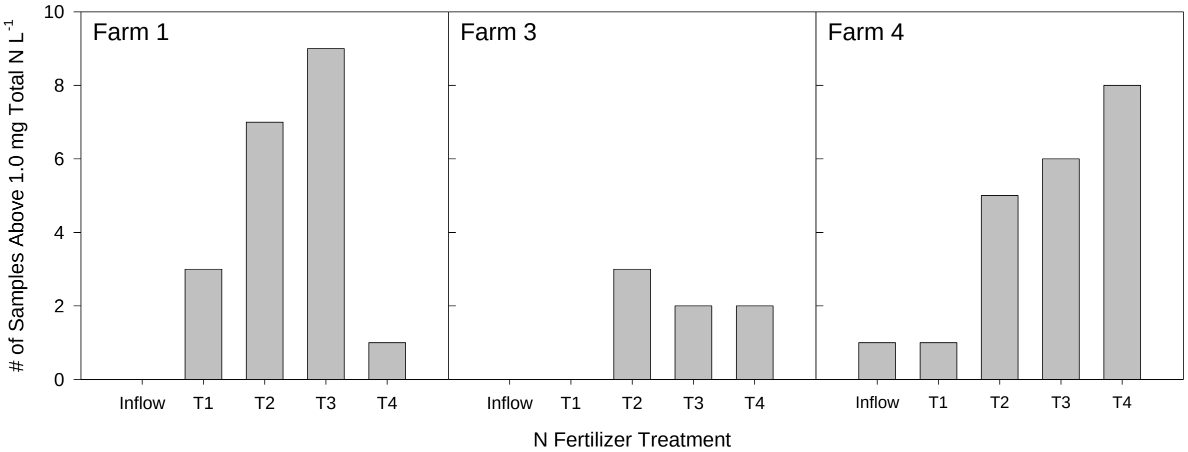

Figure 9. The number of outflow water samples exceeding 1.0 mg total N L^{-1} at each farm.

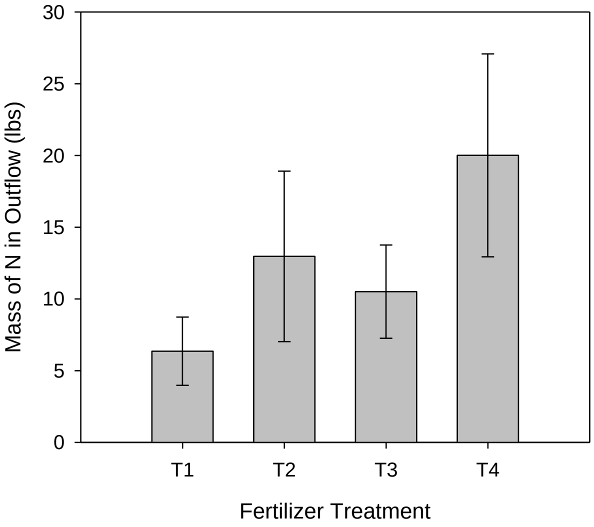

Figure 10. Fertilizer treatment effect on total N export in effluent water (N expressed as lbs N summed over 13 sampling events)

Nitrogen export from the plots under different N fertilization treatments was estimated by using measured flow rates out of the plots, the concentration of total N in the exiting water, and summing by treatment across the 14 sampling events (for the FBM and PCU fertilizer treatments, data for the first sampling point were excluded because the water flow out of the patch was restricted according to recommended practice). Results in Figure 10 show that large variation in calculated N export from the fertilized plots existed, especially for the FBM and farmer practice treatments. Nonetheless, N export was significantly higher ($P<0.05$) from the farmer practice plots (T4) in comparison with the plots that received no N fertilizers (T1). On the other hand, N export from FBM and PCU fertilizer plots was not significantly different from the 0 N plots. Furthermore, N export from the farmer practice treatment was significantly higher than N export from the PCU treatment ($P<0.1$).

Fertilizer treatment effects on nutrient uptake and N recovery by taro plants

Nitrogen uptake by the taro plants showed large variability across the three farm sites (Fig. 11A), but generally showed higher uptake values in the fertilized plots at Farm 4 compared with Farms 1 and 3. The FBM and PCU fertilizers improved N uptake by 31% and 41%, respectively, compared to the farmer practice at Farm 1, but showed smaller improvements at Farm 4 (19%

and 6%, respectively) (Fig. 11A). In contrast, at Farm 3 the FBM and PCU fertilizers reduced N uptake by 30% and 12%, respectively, compared with the farmer practice.

Nitrogen recovery expressed as ANR was low in all treatments with similar values observed across the three fertilization treatments (Fig. 11B). In the three fertilizer treatments, ANR was approximately 15%, which is within the reported ANR values for rice grown under flooded conditions (10-40%), but considered very low. Low ANR in flooded agricultural systems is not unusual due to the multiple N transformation pathways leading to loss including ammonia volatilization (loss of dissolved NH_4^+ to NH_3 gas), denitrification (microbial conversion of dissolved NO_3^- to N_2O/N_2 gas under anaerobic conditions), and run-off in the effluent flood water. The relative contributions of each loss pathway are difficult to predict and measure in the field, and were not directly measured in this experiment. Nitrogen loss through ammonia volatilization can be very high [up to 60 % of added N (Ghosh and Bhat, 1998)] especially when fertilizers such as urea are broadcast into water with pH above 7.4. On average, flood water pH was consistently above 7.4 in all treatments during the first four months of the taro crop indicating that potential N loss to ammonia volatilization was high early in the crop cycle. Nitrogen loss through the ammonia volatilization pathway was especially likely for the farmer practice treatment because urea was applied directly to the alkaline surface water. Under such circumstances the urea hydrolyzes rapidly to NH_4^+ and then at high pH is easily volatilized to NH_3 gas. Nitrogen loss through volatilization in the FBM and PCU treatments was likely reduced because the fertilizers were incorporated into the soil sediment reducing the movement of NH_4^+-N into the surface water. The data in Figure 6 showing large reservoirs of NH_4^+ in the soil suggest that N applied into the subsoil is protected against rapid loss through volatilization. After four months the pH of the flood waters in all plots was consistently below 6.5 significantly reducing the likelihood of N loss to ammonia volatilization.

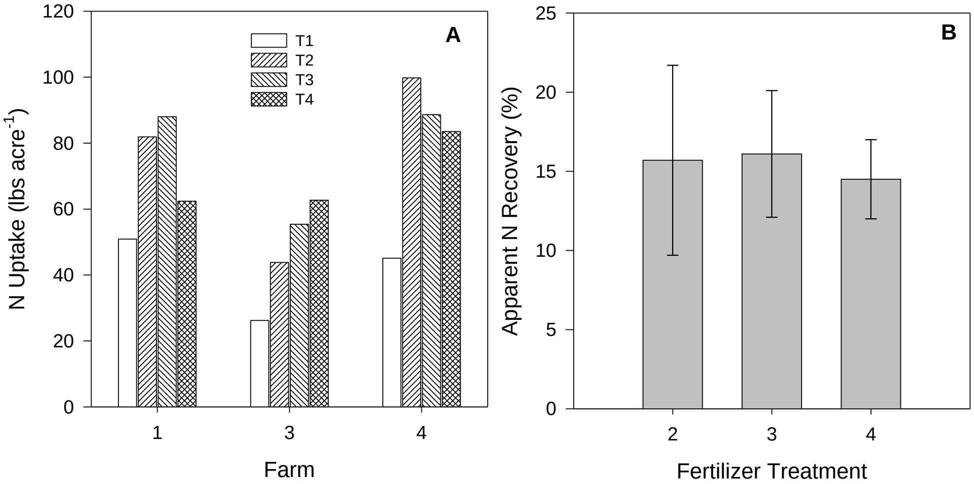

Figure 11. Fertilizer treatment effects on taro N uptake at each farm (A) and ANR (B).

Denitrification of N fertilizers can be substantial in flooded soils and contribute to losses ranging from 20 to almost 70% of applied N (De Datta, 1981). For denitrification to occur N must be in the NO_3^- form. Once applied to the soil N in the conventional urea fertilizer is rapidly hydrolyzed into NH_4^+, released more slowly as NH_4^+ in the PCU material, and mineralized relatively rapidly into NH_4^+ for the high N organic FBM. If the NH_4^+ remains in the anaerobic subsoil and does not diffuse into adjacent aerobic soil regions, further transformations will not occur and it will be available for plant uptake. However, if the NH_4^+ diffuses into the aerobic surface sediment or aerobic regions surrounding taro roots, it is subject to microbially mediated nitrification reactions which convert it into NO_3^-. The NO_3^- can be used by plant roots, but it can also diffuse back into the adjacent anaerobic soil, be denitrified and lost as N_2O or N_2 gas. Recent experimental work at UHM has shown that subsurface applied NH_4^+ in a whole core taro experiment is readily nitrified to NO_3^- in the aerobic soil regions adjacent to taro roots and then rapidly lost to denitrification. These experiments demonstrated that the coupling of nitrification and denitrification of NH_4^+ in the taro rhizosphere accounted for between 40 to 68% N loss (Penton et al., 2013). This process may be responsible for the large N losses and explain the low ANR observed in the FBM and PCU fertilizer treatments where a large reservoir of NH_4^+ was present in the subsoil during the first five months of the taro growing cycle. The presence of an aerobic taro rhizosphere coupled with a plentiful source of subsoil NH_4^+ satisfy the conditions needed for the loss of fertilizer N by the coupling of nitrification and denitrification.

Cost Benefit Analysis

A partial cost benefit analysis assessed the effect of the fertilizer strategies economic returns to the farmers. The following values were used in the analysis: 1) the experimentally derived taro yield values (lbs/acre); 2) 67¢/lb as the current market value of fresh taro[1]; and 3) fertilizer costs[2] of 48¢/lb for urea, 30¢/lb FBM, and 68¢/lb PCU[3]. All fertilizers were applied at a rate consistent with 480 lbs N per acre as described above. The data in Table 3 show mean net return and the standard deviation calculated across each fertilizer treatment at Farm 1, 3, and 4. The PCU fertilizer treatment showed the highest mean return with the lowest variability across the three farm sites. The farmer practice and FBM fertilizers showed large variability. Farmers generally prefer predictable consistent results. The PCU fertilizer material appears to be the most cost-effective option, primarily because it behaves consistently across sites. A more complete cost benefit analysis that includes labor costs may increase the attractiveness of the PCU fertilizer because there was only one application event for this fertilizer. Labor costs associated with monthly applications of urea in the farmer practice further reduce returns to the farmer. The very low yields in the FBM treatment at Farm 4 had a strong adverse effect on net return. When

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[1] Farm gate price (Hawaii Agricultural Statistics (2011)

[2] All prices as of April 23, 2013 through direct contact with BEI Hawaii (urea), Island Food Commodities, Inc. (FBM), Agrium, Inc. (PCU), and include shipping for the FBM and PCU products. All fertilizer prices are subject to change based on shifting market value.

[3] It must be noted that when fertilizer cost was expressed a per unit N basis, FBM was most expensive ($3.75/lb N) followed by PCU ($1.58/lb N) and urea the cheapest ($1.04/lb N).

Table 3. Results of a partial cost benefit analysis comparing the effects of fertilizer treatment on net return to the farms.

Treatment	Farm	Yield lb/acre	Gross Return $/acre	Net Return[a] $/acre	Mean Net Return $/acre
Farmer Practice	1	16,607	$11,127	$10,626	$14,320(±$3,333)
	3	23,482	$15,733	$15,232	
	4	26,272	$17,602	$17,102	
FBM	1	22,461	$15,049	$13,249	$11,571(±$6,583)
	3	28,287	$18,952	$17,152	
	4	9,120	$6,110	$4,310	
PCU	1	25,864	$17,329	$16,579	$15,925(±$567)
	3	24,434	$16,371	$15,621	
	4	24,366	$16,325	$15,575	

[a] Net return is a partial return representing the subtraction of fertilizer cost from Gross Return. Values in parentheses represent the standard deviation.

Farm 4 was removed from the calculation, net returns to the farmer improved to $15,200 (±$2,760), although this net return was still lower than the PCU treatment, and the variability remained relatively high.

Interpretation and Significance

Contrary to expectations, the PCU fertilizer behaved more like a conventional urea fertilizer releasing on average 85% of applied N within the first 30 days after application (mean of the three farms pooled together). The organic fertilizer showed a slower release rate, but still released close to half its N (43%) to the soil in the first month. Despite the rapid release rate associated with both fertilizers, they both produced a large reservoir of NH_4^+ in the soil that persisted up to 200 days after application. The reservoir of soil NH_4^+ represented a long term source of plant N during the vegetative growth stage of taro when N is most needed. While enhanced storage of N in the soil did not translate into improved N use efficiency (Fig. 11), it likely played a role in reducing N export to the Hanalei River (Fig. 10). The potential to reduce N loading into the river system by applying PCU fertilizer was quantified in this experiment, and represents an important environmental benefit with implications for mitigating the degradation of freshwater resources and near-shore coastal ecosystems. The environmental benefit does not come at a cost to the farmer since yields remained stable and net returns to the farmer were equal to or greater than the current practice.

Accounting for N for the current farmer practice treatment was problematic. Urea applied into the flood waters did not have a strong effect on soil NH_4^+ in comparison with the plots receiving no N fertilizers (T1) except on two occasions where the farmer practice treatment produced significantly higher NH_4^+ concentrations (Fig. 12). This combined with the low N use efficiency for the farmer practice treatment, suggests that the N was lost in the water column either through volatilization or export in the effluent water. Overall, the water sampling data indicated that the farmer practice treatment had a significantly higher tendency to export N to the river system than the 0N check and PCU fertilizer treatments. However, a more intensive water sampling procedure is required to better characterize the fate of urea applied to surface waters.

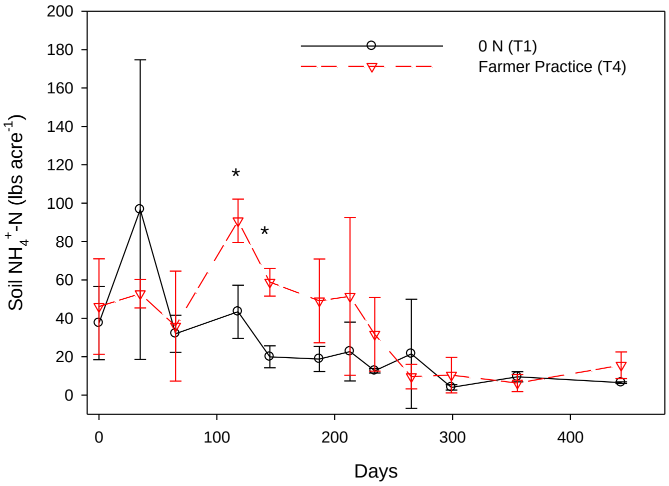

Figure 12. Soil reserves as affected by farmer practice applied urea fertilizer in comparison with the 0N check treatment. Symbols represent mean concentrations pooled across farms and error bars are one standard deviation. * denotes significant difference compared with 0N plots ($P<.0.05$).

Conclusions and Recommendations

The experimental results showed that varying the source of N fertilizer did not have a significant benefit to taro yield or N use efficiency largely because soil N reserves and yield response to the three fertilizers were not consistent across the three farms. At Farms 1 and 3, the FBM and PCU fertilizers tended to increase taro yields compared with the farmer practice providing some evidence for potential benefits to the farmer. At Farm 4, however, the farmer practice produced the best yields and FBM growth was especially poor. Excessive rainfall resulting in flooding and heavy disease pressure from *Phytophthora* infestation may have led to the below average yields and varied response across farms.

In terms of N storage potential, the PCU and FBM fertilizers showed promise in maintaining applied N as NH_4^+ in the root zone during the peak taro N requirement period, and simultaneously reducing N loading to the river system with important implications for protecting fragile freshwater and marine ecosystems from degradation. In contrast, the current farmer practice showed the highest likelihood to contribute excess N to the river system. The PCU and FBM fertilizers achieved the environmental benefit of protecting aquatic resources from N contamination while still maintaining taro yield and benefit to the farmer.

From an economic perspective, the partial budget favored the use of the PCU fertilizer because it showed the greatest potential to provide consistent returns to the farmer. Overall, consistent returns to the farmer combined with potential to reduce N contamination of the downstream environment are incentives for farmers to consider PCU as a viable fertilizer option. Results from the experiment demonstrate that adoption of a controlled release fertilizer can maintain consistent economic returns to the farmer, potentially reduce labor costs, and provide measurable benefits to the environment.

The FBM material compared favorably with other fertilizers and showed potential as a viable organic fertilizer for wetland taro production. Some of its positive attributes include the provision of a lasting supply of plant available N, potential to supply other essential plant elements such as P and Ca, potential benefits to soil quality due to its organic nature, and potential reductions in labor due to a single pre-plant application. In this experiment, however, the lack of a consistent yield response across all three sites and its higher cost ($1,800 /acre compared to $500/ac and $750/ac for the conventional urea and PCU, respectively) made it a less attractive option. The application method and timing used for the FBM fertilizer was not ideal and may partly explain uneven results observed in the experiment. Ideally, the FBM should be tilled into a dry taro field and left for two weeks before flooding. The initial aerobic phase immediately following application facilitates the decomposition process and minimizes the build-up of potential toxic intermediate decomposition products that accumulate under anaerobic conditions. Due to the experimental design and unique set-up conditions for this experiment, the FBM was applied directly to flooded soil. The plots were left to sit for 10 days before planting, and the decomposition under anaerobiosis clearly had created less than ideal conditions for planting. Potentially adverse soil conditions persisted during the first month, and taro growth was somewhat delayed at Farms 1 and 3, but recovered during the second month. At Farm 4, where water flow was lowest, taro growth was especially poor and never recovered resulting in the very low final yields. When the FBM is applied correctly to a drained taro patch as described above, taro yields exceeding 50,000 lbs per acre have been recorded at farms on Oahu demonstrating its value as a locally available organic fertilizer.

Up to now, alternatives to urea for N fertilization in flooded taro have not been considered based on economic and practical questions. Results from this experiment indicate that the Duration® PCU product from Agrium Technologies may be economically viable alternative to conventional urea with the added benefit that it will reduce potential N contamination of fragile downstream aquatic resources. While the results do not show significant taro yield benefits to the farmers, farmers do not incur an economic penalty for the added environmental benefits. We recommend that controlled release fertilizers continue to be tested to confirm that net returns are higher or similar to conventional fertilization over time. The next phase of research should address the following:

1. Can fertilizer application rates be decreased using a controlled release fertilizer due to observed long term storage of N in the root zone?
2. Confirm lower N export from controlled release fertilized fields with a more intensive water sampling design.

References

De Datta, SK.1981. Principles and Practices of Rice Production. Wiley, 618 pp.

Ghosh, B. C. and R. Bhat (1998). "Environmental hazards of nitrogen loading in wetland rice fields." Environmental Pollution 102(1, Supplement 1): 123-126.

Penton, C.R., J.L. Deenik, B.N. Popp, G.L. Bruland, P. Engstrom, D. St Louis, G.A. Brown, and J. Tiedje. 2012. Importance of sub-surface rhizosphere-mediated coupled nitrification-denitrification in a flooded agroecosystem in Hawaii. Soil Biology and Biochemistry. 57: 362-373.

U.S. Geological Survey, 1999, The Quality of Our Nation’s Waters—Nutrients and Pesticides: U.S. Geological Survey Circular 1225, 82 p.