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MACRONUTRIENT PROFILES OF WETLAND PLANTS CONSUMED BY THE HAWAIIAN MOORHEN (*GALLINULA CHLOROPUS SANDVICENSIS*)

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Abstract: Understanding the nutritional quality of wildlife foods is important for management and conservation efforts. We report the gross energy and macronutrient content of 10 plant species consumed by endangered Hawaiian Moorhens (*Gallinula chloropus sandvicensis*) along with gross energy and macronutrient content of three plant species not known to be consumed by moorhen. We also report the same information for *Urochloa mutica* that is consumed when it is < 10 cm tall, but not when it is taller. We also compared macronutrient composition of plant species collected from sites with different soil moisture levels. Energy density, fat, ash, nitrogen, protein, carbohydrates, and fiber of these wetland plants were similar across soil moisture categories, but differed among plant species. We tested for rank consistency of nutrient values across species to determine if some were consistently high across measures, and we tested whether there were differences in energy and protein content between natives and non-natives, and between species consumed versus not eaten. Rank values of macronutrients were inconsistent across species, and we found no differences in energy or protein across groups of species. Information on Hawaiian Moorhen nutritional requirements and the species' ability to metabolize these different plants will help inform wetland managers.

Key Words: endangered species, energetics, food value, forage, Hawaiian waterbirds, moist-soil management, nutritional value

INTRODUCTION

Nutritional ecology is central to a wide range of key issues in population biology, such as carrying capacity (Hobbs and Swift 1985, Guthery 1999), over-winter survival (Goss-Custard et al. 2004), habitat selection (Madsen 1985, Buchsbaum and Valiela 1987, Gill 1996), and migration (McWilliams et al. 2004, Pierce and McWilliams 2005). Nutritional ecology also plays a vital role in species management, particularly for game birds (e.g., Leopold 1933, Frederick et al. 1987, Krapu and Reinecke 1992, Bowyer et al. 2005). Although there has not been widespread incorporation of nutritional ecology into management efforts for threatened and endangered species, it has been critical for the management of at least a few (e.g., Korschgen 1962, James et al. 2004, Houston et al. 2007), and could play a larger role for others. An important first step for integrating nutrition into population ecology, and for evaluating and managing population limitation by nutritional resources, is knowledge about the nutritional value of the food items being consumed (Servello et al. 2005).

Our goal was to determine the macronutrient composition of plants eaten by the endangered Hawaiian Moorhen (*Gallinula chloropus sandvicensis*) so that we could assess which plants might provide better quality forage for the birds. It currently is unknown if forage quality or quantity is a limiting factor for moorhen populations, but increasing habitat quality and quantity are primary delisting criteria for endangered waterbirds in Hawaii, including the moorhen (Griffin et al. 1989, U.S. Fish and Wildlife Service 2005). Focusing management on increasing native plant species with high food value should benefit Hawaiian Moorhen populations, which currently number in only the hundreds range-wide (DesRochers et al. 2008).

Hawaiian Moorhen are primarily herbivorous, with plant tissue comprising up to an estimated 95%

of gut contents (Telfer and Woodside 1977, Broshears and Parrish 1980). This is consistent with findings for other Common Moorhen subspecies (Broshears and Parrish 1980, Cramp and Simmons 1980, Greij 1994). Although other Common Moorhen subspecies increase consumption of animal matter during breeding (Bannor and Kiviat 2002), the extent to which Hawaiian Moorhen seasonally supplement their herbivorous diet is unknown. Moorhen dependence on herbivory is further supported by the observation that their gastrointestinal structure and physiology are well-adapted for an herbivorous diet (Ziswiler and Farner 1972, DeGolier et al. 1999). Consequently, we focused our assessment on 11 plant species that moorhen are known to forage on throughout the year in a key waterbird wetland complex on Oahu and another plant species that moorhen have been observed consuming at two other wetland locations. These plants represent a subset of food plants that Hawaiian Moorhen are known to consume throughout their limited range because moorhen forage on some different plant species in other wetland locations such as Hanalei National Wildlife Refuge on Kauai (Gee 2007). Some of the food plant species located there such as *Cyperus difformis*, *Eleocharis obtusa*, and *Schoenoplectus juncoides* were absent from our study sites.

The primary objectives of this study were to: 1) compare the macronutrient composition of plant species eaten and those not eaten by Hawaiian Moorhen, 2) determine the extent to which macronutrient composition of plants changed with general soil moisture conditions and differed between native and non-native plant species, and 3) assess which plants may provide better quality forage for the birds and therefore might be the focus of wetland management for Hawaiian Moorhen and other avian herbivores such as the endangered Hawaiian Coot (*Fulica alai*) (U.S. Fish and Wildlife Service 2005). Two of the comparisons we made were of gross energy and protein content because acquiring energy and protein can be challenging for herbivores (Prop and Vulink 1992). Energy and protein can be of particular relevance in the conservation of herbivores (Tracy et al. 2006). We also discuss the important next steps towards developing best management practices for forage production for the Hawaiian Moorhen.

METHODS

Study Area and Plant Collection

We collected plants from wetland impoundments at James Campbell National Wildlife Refuge (James Campbell), on the North shore of Oahu (21° 41′ N; 157° 55′ W), except *Egeria densa* was collected in Waimea Valley, also on Oahu (21° 38′ N; 158° 63′ W). We harvested above-ground tissue from 11 different food plant species known to be consumed by Hawaiian Moorhen, and three plant species that are very common in wetlands where moorhen are present but to our knowledge are not consumed. One of the consumed species that we sampled, *Urochloa mutica*, is not eaten once it gets taller (> 10 cm), so we sampled tissue from both taller and smaller plants. Food plants were distinguished from non-food plants based on personal observations of feeding habits during 16 years of field observations at the Oahu National Wildlife Refuge Complex (M. Silbernagle, U.S. Fish and Wildlife Service, unpubl. data), four years of observations at numerous wetlands on Oahu (D. DesRochers, unpubl. data), and a report by Fredrickson et al. (unpubl. document) that moorhen forage on *Echinochloa crus-galli*. Additionally, due to constraints of working with endangered species we were unable to compare relative food preferences through captive feeding studies, and visual analyses of gut contents from salvaged Hawaiian Moorhen proved uninformative (B. Rameyer, U.S. Geological Survey, unpubl. data). Taxonomic nomenclature of vegetation follows Erickson and Puttock (2006).

Where available, we gathered plants from three general soil moisture levels: standing water, moist soil, and dry soil because some plants tolerate a range of hydrological conditions (Erickson and Puttock 2006) and their nutritional value may differ depending on these conditions (Kozlowski 1984, Schat 1984). We determined general soil moisture levels using U.S. Department of Agriculture methods (1998). Not all plant species occurred in all three soil moisture levels, which resulted in the following sampling distribution: three plant species were available from moist soil sites, two species were available from moist soil and wet soil conditions, two species were available from moist soil and dry soil levels, two were available from only wet soils, and one species was available from all three soil conditions. We harvested all samples from impoundments with fresh water conditions (salinity: 0–1 ppt); and we sampled two species that also occurred in saline conditions (salinity: > 20 ppt). Wetland salinity was measured with a SLT 160 Reichert Temperature Compensated Salinity Refractometer. We harvested only those plant parts (e.g., leaves, seeds, or stems) that we had observed moorhen consuming. Plants were collected from randomly placed 0.25 m^2 plots, following methods in Brower et al. (1998). Briefly, aboveground parts of each target plant species in each plot were clipped and placed fresh in separate bags and stored on ice for transportation to drying ovens. Where possible, sample plots were located in separate impoundments. For *U. mutica*, the plant species that we have not seen consumed by moorhen once > 10 cm tall, we harvested leaves from plants smaller than, and exceeding, this height. For two of the three apparently non-food plant species (*Heliotropium curassavicum* and *Paspalum vaginatum*), we harvested both the green vegetative tissue and flowers. For the third species, *Fimbristylis miliacea*, we collected only the seed heads because moorhen typically forage on the seed-bearing structures of mature sedges of other species (M. Silbernagle, pers. obs.).

At a laboratory at the University of Hawaii, we followed standard procedures for processing harvested material (Servello et al. 2005). We measured total wet weight of all harvested material from each plot before drying it in an oven at 45°C for at least 48 h. After drying, we removed plant material not known to be consumed by moorhen, such as seed husks and stalks, and we re-weighed the remaining plant tissue to determine dry weight. Finally, we pulverized the sample tissues in a Wiley Mill until the samples could pass through a 0.5 mm screen.

We conducted nutrient content analyses in duplicate for each plot per species per soil moisture class. Occasionally there was an insufficient quantity of plant material for all analyses, in which case we combined material from different plots within a given soil moisture type. We assayed the following nutritional components for each tissue sample for each soil-moisture category: energy density (kcal/g), and percent fat, ash, nitrogen, crude protein, fiber, and carbohydrate. Energy content was determined using a Parr 1266 Adiabatic Bomb Calorimeter (Gessman 1987). We used a Soxhlet apparatus and petroleum ether extraction to determine fat content (Maynard et al. 1979). We interpret these fat content data with caution because this solvent extraction removes lipids from plants that are nutritionally important to birds, along with resins, waxes, and volatile oils that have little or negative nutritional value (Servello et al. 2005). Ash content was determined by burning samples in a muffle furnace at 550°C for 24 h (Pierson and Stack 1988). Nitrogen content was determined using a Carla Erba NA 1500 Elemental Analyzer, and we calculated crude protein content by multiplying nitrogen content (expressed as a percentage of dry matter) by 6.25 (Servello et al. 2005). Percent carbohydrate content was calculated as 100 − (percent fat + percent ash + percent crude protein) (Servello et al. 2005). We used the detergent analysis system to measure total fiber content of the various foods and targeted presumed non-food tissues (Goering and Van Soest 1970). Specifically, we used the amylase-treated Neutral Detergent Fiber (aNDF) method (Mertens 2002) to measure total fiber (combined hemicellulose, cellulose, lignin, cutin) as recommended for wildlife studies (Servello et al. 2005). By definition, the total carbohydrate content includes aNDF and soluble carbohydrates although we did not separately estimate soluble carbohydrates because it includes highly digestible carbohydrates (e.g., starch, sugars) along with some unknown quantity of secondary compounds that may be anti-nutrients (Servello et al. 2005). We report both percent carbohydrates and percent fiber because we wanted to know the extent that fiber contributed to the overall carbohydrate content. Dry weight of each sample was determined by drying a subsample at 105°C and hot weighing (Goering and Van Soest 1970). We report ash-free total fiber (aNDF OM) because correcting for the ash in the aNDF improved consistency and accuracy in comparisons across laboratories and different animal feeds (Mertens 2002).

We compared each nutritional component separately across soil types and species using analysis of variance (ANOVA) in the MIXED procedure of SAS v.9.1 (SAS Institute 2003). A multivariate ANOVA would have been preferable, but because we had insufficient sample sizes to generate a robust covariance matrix, we used only ANOVAs for the analysis. Because we found no differences in nutritional components across soil types (see Results), we pooled values across soil types within each species. We then used individual ANOVAs as just described to compare each nutritional component separately across species. We used Tukey-Kramer's *post hoc* test for pair-wise comparisons if needed after each ANOVA. We excluded samples from analyses if $N \leq 2$. Following Romero and Reed (2008) we used ANOVAs to test for the consistency of ranks across all species in an attempt to identify consistently high-quality food plants. We also tested whether there were differences in rank consistencies and energy and protein content between non-native and native plant species, and between plants that were eaten versus those not consumed by moorhen. We used a t-test (SAS Institute 2003) for comparing energy and protein contents. We also calculated a repeatability statistic (r) as suggested by Lessels and Boag (1987) that describes the amount of variation in rank across versus within individuals. We assumed that the ranked value for each nutritional component was accurate despite small sample sizes.

Table 1. Energy density (kcal/g dry weight ± SD) and % (± SD) macronutrient content of A) wetland plant species consumed by Hawaiian Moorhen (*Gallinula chloropus sandvicensis*) and B) plants not known to be consumed by Hawaiian Moorhen. N = number of samples. Soil moisture refers to the hydrological state of the soil at time of sampling. Native refers to whether or not the species is native to Hawaii. Fiber content, expressed as a percent of the dry weight of the initial sample, is corrected for ash content. All plants were collected from James Campbell National Wildlife Refuge, Oahu, Hawaii, except for *Egeria densa* which was collected from Waimea Valley, also on Oahu. The same letters within a column for a nutritional category indicate non-significant Tukey-Kramer's *post hoc* comparisons ($\alpha = 0.05$).

Species	Plant part	Soil moisture	Native	N	Energy Density	% Fat	% Ash	% Crude Protein[1]	% Carbohydrate[2]	% Ash-free total fiber (aNDF OM)
A										
Batis maritima	leaves	wet (20 ppt)	no	4	2.1 ± 0.3	1.0 ± 0.2	37.4 ± 8.3	9.6 ± 1.3	51.9	19.3 ± 2.4
		moist	no	5	1.9 ± 0.2	1.1 ± 0.3	41.6 ± 7.6	9.0 ± 1.1	48.4	20.5 ± 2.5
Total				9	2.0 ± 0.2 (i)	1.1 ± 0.2 (dehij)	39.7 ± 7.7 (a)	9.3 ± 1.2 (bcdefgh)	49.9 (k)	20.0 ± 2.4 (k)
Bolboschoenus maritimus	seeds	moist (20 ppt)	yes	2	4.4 ± 0.1	1.9 ± 0.3	2.7 ± 0.1	9.1 ± 1.4	86.3	60.0 ± 3.0
	seeds	wet	yes	3	4.3 ± 0.1	2.0 ± 0.7	4.5 ± 1.8	9.8 ± 1.8	83.6	67.9 ± 3.4
	seeds	dry	yes	5	4.4 ± 0.1	2.4 ± 0.5	2.8 ± 0.9	8.6 ± 1.1	86.1	59.3 ± 5.7
Total				10	4.4 ± 0.1 (b)	2.2 ± 0.5 (bcde)	3.3 ± 1.3 (hijk)	9.1 ± 1.3 (bcdefghi)	85.4 (ab)	62.4 ± 5.8 (bcde)
Cynodon dactylon	seed stalks	dry	no	4	4.1 ± 0.2 (bcd)	1.2 ± 0.4 (bcdefghij)	8.0 ± 1.6 (cdefghij)	10.1 ± 3.5 (bcdefg)	80.7 (abc)	71.9 ± 4.6 (a)
Cyperus javanicus	seed stalks	moist	yes	2	4.1 ± 0.0	3.2 ± 1.8	8.9 ± 1.6	7.6 ± 1.1	80.3	58.4 ± 3.4
		dry	yes	3	4.2 ± 0.1	2.2 ± 0.3	10.7 ± 0.6	7.6 ± 0.5	79.6	57.3 ± 1.1
Total				5	4.2 ± 0.1 (bc)	2.6 ± 1.1 (ab)	10.0 ± 1.3 (cdef)	7.6 ± 0.7 (cdefghijk)	79.9 (abcd)	57.6 ± 1.1 (cdefghi)
C. polystachyos	young shoots	moist	yes	4	3.7	2.3 ± 0.5 (abcde)	14.3 ± 5.5 (c)	16.9 ± 6.3 (a)	70.6 (efghi)	54.0 ± 2.6 (fghi)
	seed stalks	moist	yes	4	4.2 ± 0.2	3.3 ± 0.7	9.6 ± 1.8	8.5 ± 0.8	78.6	60.1 ± 2.6
		dry	yes	4	4.1 ± 0.1	3.4 ± 1.5	9.8 ± 0.7	8.8 ± 0.8	78.0	59.3 ± 2.4
Total	seed stalks			8	4.1 ± 0.2 (bcde)	3.3 ± 1.0 (a)	9.7 ± 1.3 (cdefg)	8.7 ± 0.7 (bcdefghij)	78.3 (cde)	59.7 ± 2.4 (bcdefg)
Echinochloa spp.	seed stalks	dry	no	3	3.9 ± 0.1 (cdefg)	1.2 ± 0.6 (bcdefghi)	14.0 ± 1.9 (cd)	11.1 ± 1.3 (abcde)	73.7 (cdefghi)	65.1 ± 3.2 (abc)
Egeria densa	stems, leaves	wet	no	2	3.7 ± 0.2	1.5 ± 1.0	13.9 ± 0.2	19.0 ± 0.9	65.7	42.8 ± 13.1
Eleocharis geniculata	seed stalks	moist	no	1	3.9	2.3	17.7	16.6	63.3	48.4
Schoenoplectus californicus	Seeds	wet	no	4	4.5 ± 0.3	2.3 ± 0.4	3.4 ± 1.4	8.2 ± 0.8	86.1	65.3 ± 1.0
	Seeds	moist	no	5	4.8 ± 0.2	2.5 ± 0.1	2.7 ± 0.2	7.9 ± 0.8	86.8	66.2 ± 5.5
Total				9	4.6 ± 0.3 (a)	2.4 ± 0.3 (abc)	3.0 ± 0.9 (dgijk)	8.0 ± 0.7 (defghijk)	86.5 (a)	65.8 ± 3.9 (ab)
Typha latifolia	male flowers	wet	no	2	5.2 ± 0.1	3.4 ± 0.2	4.7 ± 0.0	17.5 ± 1.0	74.4	31.1 ± 0.0

Table 1. Continued.

Species	Plant part	Soil moisture	Native	N	Energy Density	% Fat	% Ash	% Crude Protein[1]	% Carbohydrate[2]	% Ash-free total fiber (aNDF OM)
Urochloa mutica	leaves, <10 cm	dry	no	3	4.1 ± 0.0 (bcdef)	1.4 ± 0.2 (bcdefg)	8.7 ± 1.0 (cdefghi)	12.8 ± 4.4 (abcd)	77.1 (bcdefgh)	59.1 ± 2.5 (bcdefgh)
B										
Fimbristylis miliacea	seed stalks	moist	no	1	3.9	1.9	16.5	8.8	72.8	64.2
Heliotropium curassavicum	stems, leaves, flowers	dry	yes	3	3.2 ± 0.1 (h)	2.3 ± 0.5 (abcd)	30.0 ± 2.2 (b)	13.9 ± 3.5 (ab)	53.8 (j)	35.7 ± 1.9 (j)
Paspalum vaginatum	stems, leaves	moist	no	5	3.8 ± 0.2 (cdefg)	1.3 ± 0.2 (bcdefgh)	11.2 ± 2.2 (cde)	10.4 ± 3.5 (bcdef)	77.1 (cdef)	60.5 ± 8.1 (bcdef)
Urochloa mutica	leaves, >10 cm	dry	no	5	4.2 ± 0.1 (bcd)	1.7 ± 0.8 (bcdef)	9.4 ± 1.2 (cdefgh)	12.5 ± 1.1 (abc)	76.4 (cdefgh)	64.8 ± 1.4 (abcd)

[1] Crude protein = % Nitrogen × 6.25 (Servello et al. 2005).

[2] % Carbohydrate = 100 − (% fat + % ash + % crude protein) (Servello et al. 2005).

RESULTS

We found no statistically significant differences in nutritional components between soil types for any of the plant species that we sampled from more than one soil moisture class ($F_{1,2\text{–}7}$ = 0.19–22.5, P = 0.20–0.99) (Table 1). In contrast, we found statistically significant differences for all nutritional comparisons among plant species ($F_{11,52\text{–}56}$ = 6.29–126.76, $P < 0.01$) (Table 1). Energy density (kcal/g) of *S. californicus* was significantly higher than that of all other plant species, and energy density of *Batis maritima* and *H. curassavicum* was significantly lower than that of all other species. Five species had significantly higher fat content than did the other species, and *B. maritima* had significantly lower percent fat content than did four other plant species. Percent carbohydrate content was significantly higher in four plant species and was significantly lower in both *B. maritima* and *H. curassavicum* compared with all other plants. Percent crude protein was significantly higher in four plant species. Percent ash content was significantly higher in both *B. maritima* and *H. curassavicum* compared to all other plant species. *Bolboschoenus maritimus* had significantly lower ash content compared with five other plant species, and *S. californicus* had significantly lower ash compared with four plant species. Four plants had significantly higher fiber contents compared to all others, young shoots of *C. polystachyos* had significantly less fiber than did five other plant species, and *Batis maritima* and *H. curassavicum* had significantly less fiber than did all other plant species. Short *U. mutica* had significantly less fiber than tall *U. mutica* but was not significantly different for other comparisons. See Figure 1 for summary comparison of % carbohydrate (defined as total % carbohydrate − % fiber), % fiber, % ash, % protein, and % fat.

Rank nutritional value was inconsistent across species for protein, soluble carbohydrates, and protein ($F_{16,31}$ = 1.31, P = 0.25, repeatability statistic, $r = 0.23$). However, *Typha* was consistently high for energy content, fat, and protein, but no other species were consistently high for other suites of macronutrients. In comparison, *B. maritima* was consistently low for energy, carbohydrates, and fiber.

Whether a plant was native or non-native ($F_{1,94}$ = 0.27, P = 0.60, $r = -2.69$) or considered a food plant versus not consumed ($F_{1,94}$ = 0.06, P = 0.80, $r = -14.61$) did not influence consistency ranks among species. Of particular potential interest, mean energy and protein did not differ between non-native and native plant species (energy, non-native: n = 6, 3.82 ± 0.92 [mean ± SD], native: n = 5, 3.94 ± 0.47, $t_9 = -0.27$, P = 0.79; protein, non-native: n = 6, 10.63 ± 1.87, native: n = 6, 11.10 ± 3.58, $t_{10} = -0.28$, P = 0.78). There was also no difference between plants that were eaten and those not consumed by moorhen (energy, eaten: n = 5, 3.90 ± 0.81, not consumed: n = 6, 3.73 ± 0.50, $t_9 = -0.38$, P = 0.71; protein, eaten: n = 6, 10.40 ± 2.92, not consumed: n = 6, 12.27 ± 1.76, $t_{10} = 1.03$, P = 0.33).

DISCUSSION

Habitat management for endangered waterbirds in Hawaii, particularly management of specific plant species, typically has relied on general recommendations to improve the quality and quantity of wetlands (e.g., Ohashi and Burr 1977, Telfer and Woodside 1977, Griffin et al. 1989, U.S. Fish and Wildlife Service 2005). Management tends to follow moist-soil management practices for waterbirds (Rundle and Fredrickson 1981, Payne 1992), rather than being the result of systematic experimentation in Hawaiian wetlands and its associated endemic waterbirds. To date there has been no systematic evaluation of the gross nutritional value of wetland food plants even though two of the endangered waterbirds on the main Hawaiian Islands are primarily herbivores (Hawaiian Moorhen and Hawaiian Coot). Consequently, our evaluation of gross energetic and macronutrient content of major wetland food plant species consumed by Hawaiian Moorhen on Oahu, as well as three common wetland plant species not known to be consumed by moorhen, provides an important first step for future waterbird management planning in Hawaii.

Macronutrient composition of the 14 wetland plants included in this study differed among plant species, but we detected little consistent covariation in fat, protein, and carbohydrate content. All plants had relatively little fat whereas some plants had a higher proportion of their carbohydrates in fiber (Figure 1), but the relationship between percent carbohydrate, including percent fiber, and percent protein was not simple. Positive relationships existed between carbohydrate and fat, and between carbohydrate and protein content, but there was no relationship across species between protein and fat contents. However, positive relationships were driven by a single influential species, *Typha latifolia*, and when that species was removed, there was no significant relationship among components. This suggests that *T. latifolia* might be a potentially good plant for moorhen, and in fact, moorhen regularly use the plant in nest construction. However, if wetland managers are unable to control hydrological conditions at a wetland, this exotic plant species can become invasive (M. Silbernagle, pers. obs.).

Our estimates of the macronutrient composition of these Hawaiian plants were similar to studies elsewhere on these plants. For example, gross energy content of *Bolboschoenus maritimus* (previously, *S. maritimus* (Browning et al. 1995)) in our study was similar to that reported by Dugger et al. (2007), and gross energy content of *C. polystachyos* and *C. javanicus* were similar to the gross energy contents of a closely related *Cyperus* species reported by Sherfy (1999). The gross energy content we report for the *Echinochloa* species also was similar to the value reported in Sherfy (1999) but lower than that reported in Cummins and Wuycheck (1971). Additionally, ash content of the *Echinochloa* species was higher than reported in Haukos and Smith (1995); our values were similar for crude protein content, but lower for fat. It is unknown whether these differences are part of normal background variation for the species, or if they represent differences in growing sites or conditions.

Although rank nutritional value of plants was inconsistent across plant species and was not clearly related to whether the plant was native or non-native, there were some apparent patterns. For example, in addition to the higher nutrition values we mentioned earlier for *T. latifolia*, we also found that sedge and rush species, including the non-native *S. californicus*, were consistently in the top 50% for nutritional values in all categories except for nitrogen and crude protein. Some non-natives, such as *B. maritima* and *H. curassavicum*, had consistently low nutritional values. The non-native *P. vaginatum* also had low energy density and fat content but had medium values of the other nutritional components relative to the other species compared. The non-native *U. mutica*, which moorhen apparently stop consuming after the plants exceed 10 cm in height, had high energy density and medium to high values for other nutritional components. Tall *U. mutica* had significantly higher fiber content than short *U. mutica* plants. However, moorhen regularly consume plants with higher fiber content than tall *U. mutica*. Surprisingly, we did not find differences in energy and protein content between either species consumed and not consumed by moorhen, nor between native and non-native plant species. These results suggest that moorhen avoid non-forage plants for other reasons. A variety of possibilities exist, such as the presence of plant defensive compounds (Buchsbaum et al. 1981, Dearing et al. 2005) or their micronutrient composition, including specific fatty acids or amino acids (Peoples et al. 1994, McWilliams et al. 2002).

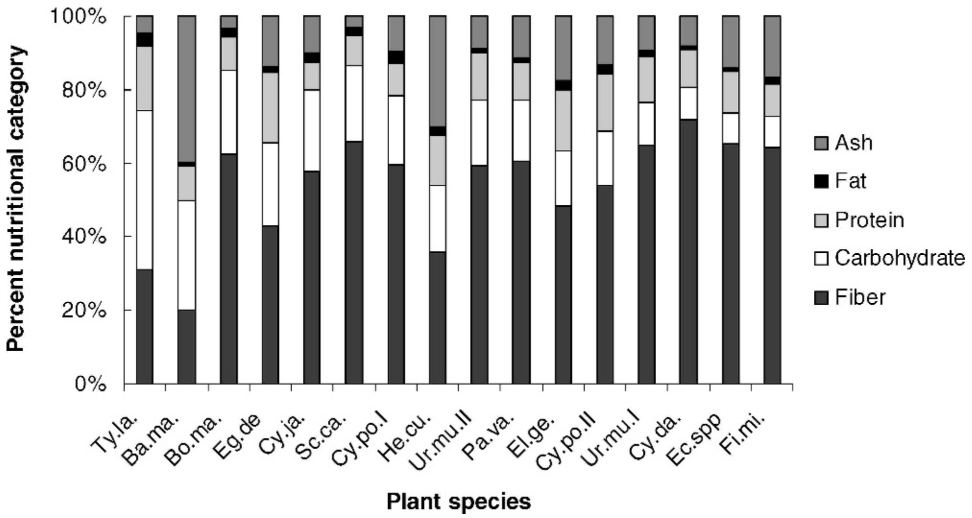

Figure 1. Percent content of fat, ash, crude protein, carbohydrate, and fiber. Values are averaged across soil moisture categories. Species abbreviations: *Ba.ma.* = *Batis maritima*, *Bo.ma.* = *Bolboschoenus maritimus*, *Cy.da.* = *Cynodon dactylon*, *Cy.ja.*= *Cyperus javanicus*, *Cy.po.* I = seed stalks of adult *Cyperus polystachyos*, *Cy.po.* II = young shoots of *C. polystachyos*, *Ec.*spp = Echinochloa spp., *Eg.de.* = *Egeria densa*, *El.ge.* = *Eleocharis geniculata*, *Fi.mi.* = *Fimbristylis miliacea*, *He.cu.* = *Heliotropium curassavicum*, *Pa.va.* = *Paspalum vaginatum*, *Sc.ca.* = *Schoenoplectus californicus*, *Ty.la.* = *Typha latifolia*, *Ur.mu.* I = leaves of adult *Urochloa mutica*, and *Ur.mu.* II = young shoots of *U. mutica*. % Carbohydrate = 100 − (% fat + % ash + % crude protein) − % fiber (Servello et al. 2005). Crude protein = % Nitrogen × 6.25 (Servello et al. 2005).

Although some non-native plants had relatively high nutritional value (Table 1 and Figure 1), most non-native plants in Hawaiian wetlands are considered undesirable (Stone 1989, Erickson and Puttock 2006). Typically, non-native plants such as *U. mutica* and *Batis maritima* become invasive, decreasing the suitability of wetlands for Hawaiian waterbirds (Scott et al. 1988, Griffin et al. 1989, U.S. Fish and Wildlife Service 2005). Consequently, although some non-native wetland plants may provide forage for Hawaiian Moorhen, they probably should not be encouraged in local wetlands unless it is well demonstrated that they do not become invasive.

Several researchers have made specific recommendations for improving vegetation cover of wetland habitat in Hawaii for endangered waterbirds through moist-soil management, which refers to manipulating water levels through systematic draw downs and flooding to encourage food production for waterbirds (Fredrickson and Taylor 1982). For example, Chang (1990) and Gee (2007) recommended tilling bare substrates and dense patches of vegetation along with manipulating water levels to encourage germination of wetland plants, and subsequent habitat use by Hawaiian Moorhen was documented. It is well-established that moist-soil management can directly influence nutritional quality and energetic value of wetland plants consumed by waterbirds (Sherfy 1999, Brasher et al. 2007). To better tie moist-soil management to moorhen management in Hawaii will require further experimental manipulations of germination requirements of food plants. There have been some investigations of environmental requirements for germination for several plant species that Hawaiian Moorhen consume. For example, *Bolboschoenus maritimus* requires warm soils, and like most obligate wetland plant species requires a surface water draw down for germination (Clevering 1995). *Cynodon dactylon* requires warm temperatures, fine texture soils, and dry soil conditions for germination (Carey 1995), and is not considered a wetland plant outside of Hawaii (Stemmermann 1981). Further relevant work on species consumed by Hawaiian moorhen can be found in Rumpho and Kennedy (1981), Clevering (1995), Gurnell et al. (2007), and Gucker (2008).

Habitat management for Hawaii's endangered waterbirds, including the Hawaiian Moorhen, is essential for conservation, and management methods will improve with greater understanding of the importance of specific wetland plant species as forage. To effectively manage moorhen food plants, we need to determine the environmental requirements of forage plant species, the impacts of moist-soil management practices on forage quality, the specific nutrient requirements of the Hawaiian Moorhen, and the moorhen's ability to metabolize different food plants. Determining true metabolizable energy and digestibility of plant protein and fiber in specific forage plants would allow direct estimates of usable energy and nutrients (e.g., Miller and Reinecke 1984, Servello et al. 2005). Once this information is available, managers could use moist-soil management practices to support the most nutritious sources of forage (Haukos and Smith 1995, Dugger et al. 2007) needed for key life-history events such as breeding (Byrd and Zeillemaker 1981) and molting (DesRochers et al. 2009).

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