
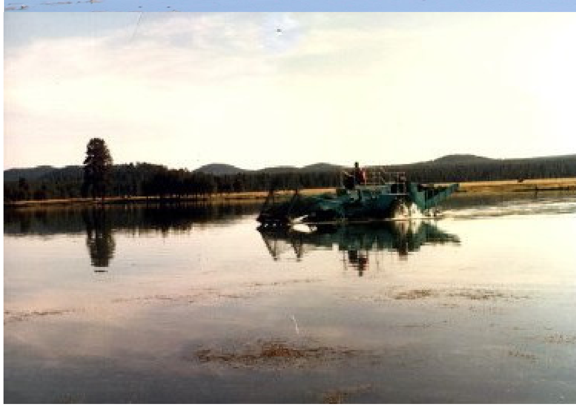


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Aquatic Plant Surveys and Evaluation of Aquatic Plant Harvesting in Arizona Reservoirs

Federal Aid in Sport Fish Restoration
Project F-14-R

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Cover photographs: *Top*--Pena Blanca Lake by Anthony Robinson; *Bottom left*—aquatic weed harvester on Sunrise Reservoir, unknown photographer; *bottom* right—aquatic weed harvester on Rainbow Lake, unknown photographer.

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Arizona Game and Fish Department Mission

To conserve, enhance, and restore Arizona's diverse wildlife resources and habitats through aggressive protection and management programs, and to provide wildlife resources and safe watercraft and off-highway vehicle recreation for the enjoyment, appreciation, and use by present and future generations.

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EXECUTIVE SUMMARY

The goal of our study was to develop information to help manage aquatic plants in Arizona's reservoirs to benefit sport fish management activities and angler access. To attain this goal we surveyed aquatic plants in reservoirs throughout Arizona and evaluated if the Arizona Game and Fish Department's aquatic weed harvesting program was benefiting the fisheries program.

We surveyed aquatic plants in 38 reservoirs throughout Arizona from 2004 through 2006 to develop an inventory of species, and to determine species distribution and composition patterns. Two non-native aquatic plant species were found during the surveys: Eurasian watermilfoil (*Myriophyllum spicatum*) was found in nine reservoirs and curly-leafed pondweed (*Potamogeton crispus*) was found at two reservoirs. Among reservoirs, the most prevalent aquatic plants were filamentous algae and another algae, muskgrass (*Chara* spp.), and the vascular plants cattails (*Typha* spp.) and hard-stem bulrush (*Schoenoplectus acutus*) followed by coontail (*Ceratophyllum demersum*), sago pondweed (*Stuckenia pectinatus*), and northern watermilfoil (*Myriophyllum sibiricum*). Within reservoirs, coontail or sago pondweed dominated the plant community at five reservoirs, northern watermilfoil at eight reservoirs and Eurasian watermilfoil at four reservoirs. Elevation and depth were significant predictors of occurrence for several species, and the number of aquatic plant taxa was positively related to reservoir surface area. Seven taxa, including filamentous algae, Eurasian watermilfoil, curly-leafed pondweed, coontail, sago pondweed, spiny naiad (*Najas marina*), and northern watermilfoil, are probably the best targets for management because they had high prevalence and percent composition in Arizona, and hence are most likely to be considered problematic.

To evaluate if the Arizona Game and Fish Department's aquatic weed harvesting program was benefiting the fisheries program, we examined whether angler access and water chemistry differed before to after harvesting at four reservoirs during 2005 and four reservoirs during 2006. We also examined the financial cost of harvesting, the amount of fish incidentally removed during the harvesting process, and surveyed anglers at nine reservoirs to determine their attitudes towards aquatic weeds and aquatic weed control. The benefits of aquatic plant harvesting were that harvesting did result in immediate reduction in aquatic plant coverage (i.e., improved access) at most reservoirs monitored, and anglers were overwhelmingly (82%) in favor of controlling aquatic vegetation. Plus, the financial cost of the harvesting program is relatively small ($50,600/year) compared to other states where millions of dollars are spent. However, aquatic weed harvesting did not appear to have the beneficial effects on water chemistry that we expected; we did not detect decreased pH or nutrient concentrations or increased dissolved oxygen concentrations subsequent to harvesting. Aquatic weed harvesting did remove some fish, most of which were game fish, but most, if not all, were expendable young-of-year fish. Another, potentially more serious cost, was that the aquatic plant harvesting program has likely resulted in the spread of the invasive Eurasian watermilfoil to reservoirs throughout Arizona. Aquatic plant harvesting is probably a worthwhile endeavor to improve angler access and keep our angling customers satisfied. However, we strongly recommend that more effective decontamination procedures be implemented to limit the spread of invasive species.

INTRODUCTION

Aquatic freshwater plants tend to have large-scale distributions (Santamaria 2002), and at a local scale, play an important role in aquatic ecosystems. However, excessive aquatic plant densities and biomass can be considered problematic. Lembi (2003) summarized problems associated with excessive aquatic plant density as follows. Recreational activities such as swimming, fishing, and boating can be impaired or prevented. Excessive densities and biomass can also result in stunted fish growth and overpopulation of small-bodied fishes. This occurs because the production of too much vegetative cover prevents effective predation of small fish by larger fish. Excessive aquatic plant growths can also decrease localized dissolved oxygen levels, which can cause fish kills. Oxygen levels are affected by the diel cycle of photosynthesis (oxygen levels are high during the day) and respiration (night-time oxygen levels are depleted). If plant biomass is excessive, nighttime respiration by aquatic plants can consume most of the dissolved oxygen in the water within the macrophyte beds to levels less than 1-2 mg/L. Furthermore, excessive growth during the summer results in large quantities of organic matter, that when decomposed via bacteria and microbes, results in high rates of microbial respiration and thus oxygen consumption. Similar processes can occur in the winter for lakes that freeze. Snow cover over ice decreases light levels and reduces or prevents photosynthesis and oxygen production, but organic matter continues to be decomposed by bacteria, thus consuming oxygen. Other problems associated with excessive plant growth include: 1) aquatic plants provide stagnant habitat ideal for mosquito breeding, 2) certain algae can impart foul tastes and odors to the water, and can produce substances toxic to fish and wildlife, 3) plants impede water flow in ditches, canals, and culverts and cause water to back up, 4) deposition of dead organic matter can cause the gradual filling in of water bodies, 5) nutrients, particularly organic carbon and phosphorus, released from senescent plants into the water can result in algal blooms, 6) excessive growth can lower property values and decrease aesthetic appeal, and 7) invasion of nonnative plants (i.e., invasive species) can cause shifts in community structure and function that may negatively impact native animal and plant species. Aquatic plants are often managed to alleviate some or all of the above mentioned problems.

Arizona Game and Fish Department (Department) has used several techniques to manage aquatic plants in Arizona's sport-fishing reservoirs since the 1980s to help manage fisheries and improve angler access. Triploid grass carp (*Ctenopharyngodon idella*) are used to control aquatic plants in some isolated reservoirs, and in canals and some golf course ponds. Prior to 1980, the Department primarily used herbicides (diquat) to manage aquatic nuisance plants (i.e., aquatic weeds) on public reservoirs and ponds, and herbicides are still used in urban waters. However, the public objected to the use of herbicides in non-urban reservoirs (specifically Arivaca Lake) during the early 1980s, and other control measures were investigated. From 1982 through 1990 the Department used an Aquamarine H-650 Harvester, which both cut and harvested weeds. In 1985, Department acquired a Hockney HC-10 Aquatic Weed Cutter by a donation from Northern Arizona Flycasters to control aquatic weeds in a few shallow reservoirs; this piece of machinery cut the vegetation, which then had to be removed (harvested) with an attached rake or raked by hand. In 1990, the Department purchased an Aquarius Systems H-620 Aquatic Plant Harvester (which both cut and harvested weeds), to replace the H-650. A second, smaller harvester (Aquarius Systems HM-220 Aquatic Plant Harvester) was purchased in 1995. Harvesting was the primary means the Department used to control aquatic plants in non-urban reservoirs and ponds from 1982 to present. The purported benefits of aquatic plant harvesting in Arizona include: (a) improved angler access, (b) a decrease in pH which can then allow for extended periods of trout stocking during the summer, (c) greater dissolved oxygen concentrations which decrease the chance of summer kills, and (d) a decrease in nutrients which will lessen algal blooms. With respect to the latter three benefits, macrophytes are reported (Wetzel 1983, Carpenter and Lodge 1987, Carter et al. 1991) to affect pH and dissolved oxygen concentrations within the macrophyte beds, and when they senesce, result in increased nutrient levels.

The Department's regional fisheries program managers determine which reservoirs they would like harvested, and the Development Branch is responsible for harvesting aquatic plants from those reservoirs. Aquatic weeds have been harvested from 27 reservoirs and ponds since the program began. In a typical year, harvesting is done May through October, and six reservoirs (average number harvested between 1997 and 2006) are harvested, one or two of which are usually harvested twice in one year. On average during the 1997-2006 period, three reservoirs per year were harvested using the H-620 (approximately 3 weeks per reservoir) and three reservoirs per year were harvested with the HM-220 harvester (approximately 1-2 weeks per reservoir).

The H-650 was and the H-620 is used on larger and deeper reservoirs because of their greater draft, whereas the HM-220 and HC-10, because their drafts are less, are used on shallower reservoirs. Specifications for the harvesters and cutter are given in Table 1. The three harvesters can only be used on reservoirs that have a boat ramp of sufficient depth to allow launching. The Hockney HC-10 is a relatively small watercraft and can be launched on most reservoirs with a boat ramp. When the H-620 or H-650 is used, the strategy is to harvest the bulk of the vegetation in the center of the lake and then harvest the shorelines. For the HM-220 and HC-10, the strategy is to harvest as much as possible for small reservoirs, but for larger reservoirs, only boating lanes or areas around docks or near-shore recreation areas are targeted. The plant material harvested is transferred to a dump truck and taken to an approved dump site.

Table 1. Specifications of aquatic plant harvesters used by Arizona Game and Fish Department.

Harvester Model	Max. cut depth (m)	Cutting width (m)	Capacity	
			(m^3)	(kg)
Aquamarine H-650	1.52	2.44	18.4	4,536
Aquarius Systems H-620	1.68	2.74	23.5	5,371
Aquarius Systems HM-220	1.68	1.52	7.4	2,948
Hockney HC-10	1.5	3.0	---	---

The goal of our study was to develop information to help manage aquatic plants in Arizona's reservoirs to benefit sport fish management activities and angler access. Our first objective was to develop an inventory of aquatic plant species found in sport-fishing reservoirs throughout Arizona in order to determine species distribution and composition patterns. These data will help focus management actions on problematic aquatic plant species. The second objective of this study was to evaluate if the Department's aquatic weed harvesting program was benefiting the fisheries program. To address the second objective, we examined whether angler attitudes, angler access, and water chemistry differed before and after harvesting at selected reservoirs. We also examined the financial cost of harvesting, as well as the amount of fish incidentally removed during the harvesting process.

METHODS

Statewide Aquatic Plant Survey

Study Sites

Our goal was to survey aquatic plants in a minimum of one sport-fish reservoir from each of the U.S. Geological Survey watersheds in Arizona (8-digit Hydrologic Unit Code: HUC). Forty-eight of the 84 HUCs in Arizona have a reservoir or pond with sport fish present. We excluded HUCs on tribal lands, except for the Navajo and Hopi Nations where we were permitted access, resulting in 45 potential HUCs to survey. Reservoirs were targeted for the presence of sport fish and a boat ramp, but if such water bodies were not found within a HUC, water bodies without boat ramps were considered. Water bodies were randomly selected from each HUC for sampling. However, we wanted to survey all reservoirs where Arizona Game and Fish Department had harvested aquatic vegetation in the past, so in some instances, more than one water body per HUC were surveyed. Surveys were conducted June through October during the period when aquatic macrophytes are flowering to allow for easier identification.

Methods

Aquatic macrophytes were surveyed using two point-transect methods similar to the line intercept method described in Titus (1993). In reservoirs less than or equal to five meters in depth, we determined the length of the long axis by measuring it on a topographic map (TOPO! 2002), or using a range-finder in the field. We placed five transects perpendicular to the long axis of the reservoir at 1/6, 2/6, 3/6, 4/6, and 5/6 the length of the long axis (Figure 1). We surveyed 20 points along each transect, one point located one meter from the interface of water and land on each side of the reservoir and the remaining 18 spaced evenly on the transect line.

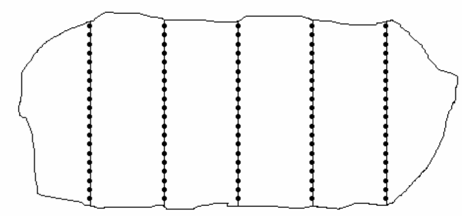

Figure 1. Diagram of transect layout for an aquatic plant survey of a shallow lake (mean depth < 5 m).

For deeper (> 5 m) reservoirs, we also used the point-transect method. Our sampling was restricted to low-gradient near-shore slopes, because we assumed these were most likely to have established vegetation. We determined locations of low gradient near-shore slopes from a topographic map (TOPO! 2002) or our own visual examination at the reservoir. We selected 10 low-gradient slope locations around the reservoir. We decided to select all stream mouths and low-gradient areas near boat ramps, because these were likely invasion areas for invasive aquatic plants. We spread the remaining sampling locations relatively evenly around the reservoir shore to get a representative sample of the reservoir. At each location, we established a perpendicular-to-shore transect originating in the approximate center of the shoreline of the low-gradient slope and extending out to the edge of the aquatic weed bed, or out to three meters deep if the water was turbid and we could not see the edge of the aquatic weed bed. We sampled aquatic plants at 10 points beginning one meter from the water-land interface, and the remaining nine located equidistant from each other.

A total of 100 points were sampled at each reservoir except at the following reservoirs: 20 points at Big Springs Pond because of its small size (0.4 ha) and at Marshall Lake one point was accidentally missed so only 99 points were sampled. Because of the large size (over 1,200 ha) of Topock Marsh, we added additional transects to acquire a better sample of the aquatic plants in this water body. At each sample point on each transect, we used a rake (Wolf Garten DO-M 35) with a three-meter-long extendable pole (Wolf Garten, Vario ZM-V3) to collect aquatic plants, which restricted our maximum sampling depth to approximately 3.3 meters. Aquatic plants were found on occasion to be at depths greater than 3.3 meters, depending on water turbidity. The rake head was lowered to the bottom and rotated 360º and then pulled to the surface (Gibbons et al. 1999). We recorded all taxa of aquatic macrophytes collected on the rake head. After all points on all transects were sampled, we did a roving survey around the reservoir to identify and record any species not found on transects. We collected a sample of each species for species identification by a university botanist. We typically took digital photographs of each aquatic plant species at each reservoir.

We identified aquatic vascular plants to species whenever possible. We did not identify all algae to species, so they were categorized into general groups (e.g., filamentous, encrusting), except for muskgrass and stoneworts, which were identified to genus. Cattails were typically identified to genus level. Terrestrial plants found along transects are not reported in this paper. For each aquatic plant species, we calculated prevalence (number of reservoirs with a species divided by the total number of reservoirs surveyed, multiplied by 100), percent frequency of occurrence (number of points with a species divided by the total number of points sampled, multiplied by 100), and percent composition (number of points with a taxa divided by the total number of points with plants, multiplied by 100). For shallow reservoirs, percent frequency of occurrence derived from our point-transect methodology provides an estimate of percent cover for each species (Madsen 1999, Elzinga et al. 2001).

We used forward step-wise logistic regression (SPSS 2003) to assess if elevation, average depth, and average area were significant predictors of species occurrence. Variables were added or removed from the models by using likelihood ratio tests with a significance level of 0.05. We assessed goodness of fit of the models by examining –2 times the log of the likelihood (-2 LL), where the best model among those considered was the model with the smallest –2 LL value (Manly et al. 2002). Elevation, average surface area, and average depth of reservoirs were obtained from a Department fisheries database. All reservoirs surveyed were included in the logistic regression analyses, except Lake Pleasant, which experiences large seasonal fluctuations in water elevations because it is a water storage reservoir, which we thought resulted in an absence of any aquatic vegetation.

To assess if our data supported biogeographic theory that the number of species increases with area, we assessed relationships between number of aquatic plant species (in categories submersed, floating, emergent, or total) found in shallow reservoirs and average surface area (hectares) with linear regression. Surface area was log transformed prior to analysis and was regressed against number of species, and in separate analyses, log-transformed number of species. We only examined shallow reservoirs to try to control for the fact that most rooted species are limited to shallow waters, and a few of the deeper reservoirs are used for flood control and have widely variable surface elevations throughout the year.

We examined associations between pairs of species with two-way contingency table analysis and the phi coefficient (Zar 1984). We restricted the analysis to species that were found at five or more reservoirs.

Evaluation of Harvesting Program

Study Sites

We monitored vegetation coverage and water quality before and after harvesting at four reservoirs during 2005 and four reservoirs during 2006. We wanted to monitor two reservoirs harvested by the large harvester (H-620) and two reservoirs harvested by the small harvester (HM-220) each year. However, because drought conditions resulted in low reservoir levels, several reservoirs were inaccessible, particularly to the larger H-620 harvester. Therefore, only one reservoir (Luna Lake) harvested with the H-620 was monitored, but it was monitored both in 2005 and in 2006. We monitored five reservoirs that were harvested with the HM-220: Pena Blanca Lake, Parker Canyon Lake, and Crescent Lake during 2005, and Parker Canyon Lake, Rainbow Lake, and Cluff Ranch Pond #3 during 2006. For each reservoir, we designated an area not to be harvested (control area) and an area that would be harvested (treatment area). We also attempted to measure the numbers of fish incidentally collected by the harvesters at these six reservoirs, but, due to time constraints, we only conducted this sampling at five reservoirs: Pena Blanca Lake during 2005, and Luna Lake, Parker Canyon Lake, Cluff Ranch Pond #3, and Rainbow Lake during 2006.

For angler surveys, we monitored angler attitudes at nine reservoirs (six were reservoirs where we monitored vegetation coverage and water quality) during 2006: Arivaca Lake, Pena Blanca Lake, Parker Canyon Lake, Cluff Pond #3, Nelson Reservoir, Crescent Lake, Luna Lake, Rainbow Lake, and Concho Lake. Our vendor did not get our kiosks constructed on time to deploy them during 2005, so we only collected angler survey data during 2006.

Aquatic Vegetation Coverage

We used aquatic vegetation coverage as a measure of angler access. The percent of the lake surface area with aquatic vegetation at or near the surface was visually estimated during each water quality survey (see below) while traveling around the lake in a boat, and the areas with plants were shaded in on a topographic map. In addition, surface area coverage of aquatic macrophytes was estimated with Geographic Information Systems (GIS) technology. With our Garmin eMAP GPS receiver turned on, we piloted the boat along the edge of the macrophytes bed, and saved the resulting track within the GPS unit. We used the reservoir shore shown on 7.5 minute series U.S. Geological Survey topographic maps (digitized into GIS) to calculate the total surface area of the lake. We used our tracks to determine the area of open water on the lake and subtracted that area from the total surface area to determine the surface area covered by aquatic vegetation. We then calculated percent of the surface area that was covered by aquatic vegetation at each lake during each survey.

Fish Kills

We used the number of dead fish observed during the aquatic vegetation surveys as a fish kill index.

Water Chemistry

We used a before-after control-treatment design, with before referring to before harvesting and after referring to after harvesting. Within each lake, we designated a treatment cove and a control cove, each of which had similar aquatic vegetation cover and similar depths; control coves were not harvested, whereas treatment coves were harvested. We measured water quality variables periodically (monthly during 2005 and every two weeks during 2006) before and after harvesting; we attempted to have at least three pre-harvesting and three post-harvesting sampling events at each lake.

Mid-Day Sampling

We established a transect across the middle of the aquatic macrophyte bed, perpendicular to the long axis of each treatment and control cove. We established two other transects in open water (open-water transects) 20-50 m from and parallel to the aquatic plant bed transects. During 2006, we decreased the open-water transects from two to one, and located it in the center of the open-water portion (area absent of aquatic macrophytes) of the lake. We measured water chemistry variables at points located on transects at 0.25, 0.5, and 0.75 transect length between 11:00 h and 14:30 h.

At each point, we measured water temperature (°C), dissolved oxygen (mg/L and % saturation), and pH at 1-meter depth with a YSI 6920 multiparameter sonde connected to a 610-DM Display/Logger during 2005, or with a Hydrolab Reporter multiparameter sonde connected to a Hydrolab Surveyor 3 during 2006. We measured alkalinity (mg/L of $CaCO_3$) of a 100-ml water sample collected from the surface with a Hach Model 16900 digital titrator kit (brom-cresol green-methyl red endpoint, sulfuric acid titrant). We measured turbidity (NTU) of a water sample collected from the surface with a HF Scientific, Inc. DRT-15CE turbidimeter. We used a secchi disk lowered into the water on the shadowed side of the boat to measure water clarity. To measure nitrate-nitrite nitrogen (mg/L) and orthophosphate (mg/L) concentrations, we collected a 100-ml sample from immediately below the water surface at each point and combined all three samples from each transect into one composite sample, and used a Hach DREL 2000 spectrophotometer to measure nitrate-nitrite nitrogen (cadmium reduction method) and orthophosphate (ascorbic acid method) of the composite sample. We did not sample nitrate and orthophosphate during 2006 because values from 2005 were highly variable and many samples had undetectable concentrations. To measure chlorophyll *a* concentrations, a 100-ml sample was collected from immediately below the water surface at each point and all three samples from each transect were combined into one composite sample. We filtered he composite-water samples onsite through Whatman 47 mm glass microfibre filters, wrapped them in aluminum foil, placed them on ice, and transferred them to a freezer until laboratory chlorophyll analysis could be performed. We used the spectrophotometric method (APHA et al. 2005) to determine chlorophyll *a* (µg/L) content of samples.

22-Hour Sonde Sampling

Because pH and dissolved oxygen measurements derived from the mid-day sampling in 2005 were highly variable and changes in levels after harvesting were not very obvious, we measured these variables every 2 h for 22 h during each sampling event in 2006 in an attempt to account for diel cycles and reduce measurement variability; 22-h sonde sampling and mid-day sampling co-occurred in 2006. We fixed a buoy in place at the mid-point of each treatment and control transect at each lake. During each sampling event, we affixed a Hydrolab Recorder sonde to the bouy such that the probes were at 1-m depth; we set the sonde to record water temperature (°C), dissolved oxygen (mg/L and % saturation), and pH every 2 h for 22 h.. We pulled the sondes the following day and downloaded data to a computer.

Analysis

We examined levels of dissolved oxygen, pH, and nutrients because they have direct impacts on fisheries and fisheries management, and aquatic plants were thought to affect levels of these variables. Summer kills occur in high elevation reservoirs in Arizona, typically as a result of extended periods of low dissolved oxygen concentrations. If aquatic plant biomass is excessive, nighttime respiration by these plants can consume most of the dissolved oxygen in the water to levels less than 1-2 mg/L, and on overcast days, oxygen can remain depleted into the daytime, thus stressing and killing fish. Therefore, we assessed if dissolved oxygen concentrations increased following harvesting. With respect to pH, the Department will not stock trout if a water body has a pH greater than 9, therefore this value was used as a criterion to judge whether harvesting allowed for an extended stocking period. Aquatic plants store nitrogen and phosphorus in their tissues, which are released when they die and decompose, which may then increase algal blooms. Therefore, we examined if nutrient levels decreased following removal of aquatic vegetation, and whether algal chlorophyll *a* concentrations increased following harvesting.

Water quality measurements for treatment and control coves by sampling event were plotted for each lake monitored and graphs were examined to determine if there were obvious changes in trends after harvesting. Data used in the graphs were means (water temperature, dissolved oxygen, pH, and alkalinity) or raw values (nitrate, orthophosphate, and chlorophyll *a* concentrations). We also used intervention analysis (SPSS 2003), a type of Autoregressive Integrated Moving Average (ARIMA) trend analysis, to assess if harvesting (the intervention) affected the trend in water chemistry measurements differently for the treatment and control coves. Autocorrelation and partial autocorrelation graphs for treatment and control groups were examined for each water chemistry variable to decide which ARIMA model to use. If treatment and control coves were similar and harvesting had an effect, then we expected water quality trends within the treatment and control coves to be similar prior to harvesting, but divergent after harvesting.

Operational Cost of Harvesting

We acquired Harvesting Completion Reports from Arizona Game and Fish Department's Aquatic Weed Harvesting Program and input data to create an electronic database. Data on Completion Reports included: lake name, operator name, date started and completed, duration and monetary cost of labor, per-diem costs, duration harvester and vehicles were operated and associated costs, hours harvester could not be operated and reason it could not be operated (e.g., thunderstorm, mechanical breakdown), miscellaneous operational costs, total cost, estimated tons or acres harvested, and harvester equipment identification number; durations were recorded in hours and costs were dollar amounts. From this data we calculated tons harvested per hour and cost per ton or acre harvested.

We graphed total cost of the harvesting program by year to assess monetary cost of the program over time. We assessed if there were relationships between hours the harvester was operated and tons harvested and total costs with Pearson's correlation coefficient (Zar 1984). We wanted to be able to assess the hypothesis that yearly harvesting would deplete the nutrients in a lake and result in less plant biomass in successive years. However, data on yearly plant coverage or biomass were nonexistent. Therefore, we addressed the hypothesis indirectly by graphing tons harvested by year at each lake and visually examining graphs to determine if there were downward trends in tons harvested from year to year.

Incidental Fish Collection
Small fish are reported to be inadvertently harvested with weeds (Wile 1978, Haller et al. 1980, Mikol 1985, Engel 1990, Booms 1999), so we examined the numbers and biomass of fish removed by harvesting. At five reservoirs, three 0.3 m^3 subsamples (a wheel barrel load) of harvested weeds were picked through and fish extracted, identified to species, counted, and weighed (g wet weight total sample by species). Monetary loss to the fishery was estimated by assigning a monetary value to each fish using American Fisheries Society's (AFS) Investigation and Valuation of Fish Kills book (AFS 1992).

Angler Use Survey
We used angler survey cards to evaluate angler opinions of aquatic vegetation and aquatic vegetation control. Five questions were presented to anglers on the angler survey card (Figure 2). Questions 1 and 2 were used to assess if aquatic vegetation affected the angler's fishing experience or prevented them from fishing entirely. Question 3 was used to assess how much of the lake was perceived to be inaccessible because of aquatic vegetation (i.e., an estimate of the aquatic plant coverage). Question 4 was used to assess angler's attitudes towards aquatic vegetation control. Question 5 was used to determine if the person was a casual angler (only fished a few times a year) or an avid angler (fished 15 or more days a year) at that particular lake.

ANGLER SURVEY ABOUT AQUATIC VEGETATION

1. How does aquatic vegetation affect your fishing experience at this lake?
   ☐ greatly hinders fishing ☐ moderately hinders fishing ☐ no effect
   ☐ moderately improves fishing ☐ greatly improves fishing
2. Does aquatic vegetation ever prevent you from fishing at this lake? ☐ yes ☐ no
3. How much of this lake is inaccessible because of aquatic vegetation?
   ☐ 0% inaccessible ☐ 1- 25% inaccessible ☐ 26-50% inaccessible
   ☐ 51-75% inaccessible ☐ 76-100% inaccessible (total or nearly total plant coverage)
4. Aquatic vegetation should be controlled.
   ☐ strongly disagree ☐ moderately disagree ☐ no opinion
   ☐ moderately agree ☐ strongly agree
5. How many days a year do you fish at this lake?____________

Month________________ **Lake name**: ____________________

Figure 2. Angler survey card used during study.

A kiosk with survey cards and a drop box was placed at each of nine reservoirs in February 2006; four reservoirs (Arivaca Lake, Pena Blanca Lake, Cluff Ranch Pond #3, and Parker Canyon Lake) were at elevations between 1,008 and 1,642 m, and five reservoirs (Concho Lake, Crescent Lake, Luna Lake, Nelson Reservoir, Rainbow Lake) were at elevations between 1,919 and 2,757 meters. Five of the reservoirs were harvested during 2006 (Cluff Ranch Pond #3, Luna Lake, Parker Canyon Lake, Pena Blanca Lake, and Rainbow Lake), the other four were harvested at least once during 2000-2005. The kiosks were visited monthly to retrieve completed cards and replenish with blank survey cards.

Responses were entered into a computer as numeric variables to facilitate statistical analyses: for question one, 1 = greatly hinders, 2 = moderately hinders, 3 = no effect, 4 = moderately improves, and 5 = greatly improves; for question two, 1 = yes and 2 = no; for question three, 1 = 0%, 2 = 1-25%, 3 = 26-50%, 4 = 51-75%, and 5 = 76-100%; for statement four, 1 = strongly disagree, 2 = moderately disagree, 3 = no opinion, 4 = moderately agree, and 5 = strongly agree. For questions 1-4, the percentage of anglers, statewide and at each lake that marked each response was calculated. Data from Crescent Lake and Concho Lake are not presented because too few anglers responded to the survey (3 and 10 anglers respectively). We assessed if angler responses to questions 1-4 at the five reservoirs that were harvested during 2006 differed during the period before harvesting from the period after harvesting. We also used Pearson's correlation (Zar 1984) to assess potential relationships among responses to the four questions and the number of days per year that an angler fished that reservoir.

RESULTS

STATEWIDE AQUATIC PLANT SURVEY

We sampled 38 reservoirs within 29 HUCs in Arizona from 2004 to 2006 (Figure 3). We did not reach our target of sampling a reservoir in the 45 available HUCs due to the drying of reservoirs in four HUCs, lack of access on tribal lands in three HUCs, rough road conditions in one HUC, and international border issues in one HUC. We did not sample reservoirs in seven other HUCs because of time and budgetary constraints. We surveyed 17 of the 27 reservoirs that have been harvested by the Department.

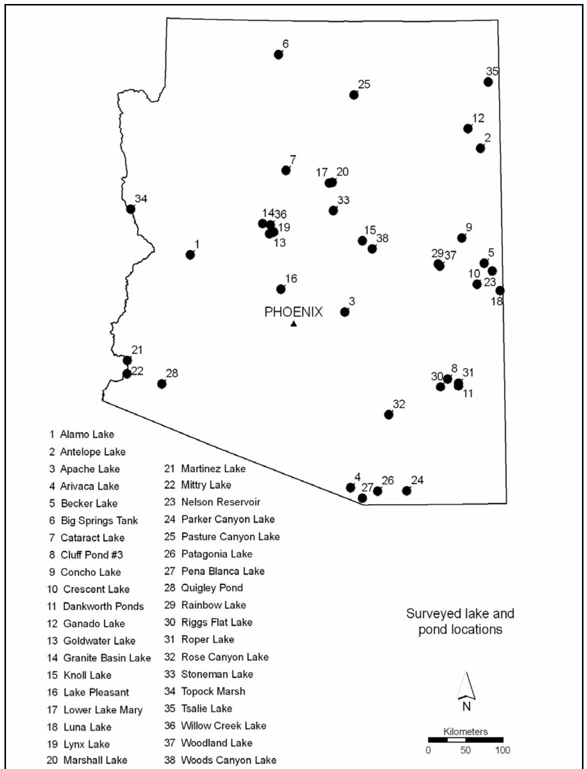

Figure 3. Map of reservoirs surveyed for aquatic vegetation in Arizona from 2004 to 2006.

During this study, the most prevalent taxa were filamentous algae, being present at 76% of the sampled reservoirs (Table 2, Appendix A1) and another alga taxon, muskgrass, found at 53% of the sites surveyed. The most prevalent vascular plant species were coontail, sago pondweed, cattails, and hard-stem bulrush, which were found in 42% to 47% of the reservoirs surveyed. Other species commonly found (prevalence 26% to 37%) in our surveys were northern watermilfoil, water knotweed (*Polygonum amphibium*), two-leaf elodea (*Elodea bifoliata*), and small pondweed (*Potamogeton pusillus*). Two non-native aquatic macrophyte species were found on transects during our surveys: Eurasian watermilfoil and curly-leafed pondweed.

Table 2. Aquatic plant taxa found in 38 Arizona reservoirs during 2004 through 2006 surveys, giving plant type (E = emergent, F = floating, S = submersed), prevalence (N_P = number of reservoirs with taxa present, and %P = percent of reservoirs with taxa present), mean percent composition (N_C = number of reservoirs with taxa found on transect points, and %C = number of points with taxa divided by total number of points with plants), and for shallow reservoirs, mean percent frequency of occurrence (N_F = number of shallow reservoirs with taxa present, and %F = number of points with taxa divided by total number of points sampled in shallow reservoirs). Also given are the minimum and maximum reservoir elevation (m), minimum and maximum average reservoir depth (m), and minimum and maximum average reservoir surface area (ha). N_P is greater than N_C when taxa were not found on transects but were found during the roving survey after transect sampling was complete. Standard deviations of means are given in parentheses.

								Prevalence		Composition		Frequency	
Taxa	Type	Min Elev.	Max Elev.	Min Depth	Max Depth	Min Area	Max Area	N_P	%P	N_C	%C	N_F	%F
Azolla filiculoides	F	1,567	1,567	15.2	15.2	8.1	8.1	1	2.6	1	7.1	1	6.0
Bacopa monnieri	E	23	23	2.4	2.4	131.5	131.5	1	2.6		.		.
Carex spp.	E	2,403	2,403	2.4	2.4	30.4	30.4	1	2.6	1	1.3	1	1.0
Carex stipata	E	2,664	2,664	13.7	13.7	4.5	4.5	1	2.6		.		.
Ceratophyllum demersum	S	23	2,403	0.9	27.4	4.0	283.3	16	42.1	16	48.0 (32.8)	13	37.0 (24.8)
Chara spp.	S	23	2,664	0.9	27.4	0.4	1295.0	20	52.6	20	21.8 (26.0)	19	17.8 (23.1)
Crypsis schoenoides	E	1,567	1,567	15.2	15.2	8.1	8.1	1	2.6	1	2.4	1	2.0
Cyperus esculentus	E	1,685	1,685	12.2	12.2	22.3	22.3	1	2.6	1	2.2	0	.
Cyperus odoratus	E	1,642	1,642	25.0	25.0	50.6	50.6	1	2.6	1	2.1	0	.
Cyperus spp.	E	55	2,168	0.9	73.2	14.2	1092.7	4	10.5	3	18.3 (28.3)	1	1.0
Echinochloa crus-galli	E	1,685	2,143	1.8	12.2	22.3	1295.0	3	7.9	1	6.7	0	.
Eleocharis palustris	E	1,488	2,403	0.9	15.2	0.4	1295.0	8	21.1	8	3.1 (2.1)	8	2.6 (1.8)
Eleocharis parishii	E	1,567	2,044	1.8	15.2	8.1	32.4	2	5.3	2	1.1 (0.1)	2	1.0 (0.0)
Eleocharis spp.	E	2,664	2,664	13.7	13.7	4.5	4.5	1	2.6	1	1.6	1	1.0
Elodea bifoliata	S	1,567	2,757	0.9	15.2	4.0	1295.0	11	28.9	11	43.5 (28.3)	11	38.3 (25.2)
Filamentous algae		23	2,757	0.9	25.0	0.4	1295.0	29	76.3	28	30.3 (29.6)	24	24.9 (26.2)
Glyceria grandis	E	2,044	2,403	1.8	2.4	30.4	32.4	2	5.3	1	2.5	1	2.0
Juncus effuses	E	2,113	2,113	13.4	13.4	2.8	2.8	1	2.6	0	.	0	.
Lemna minor	F	335	1,700	1.8	24.4	2.0	1092.7	3	7.9	3	2.9 (2.2)	2	2.5 (2.1)
Myriophyllum sibiricum	S	1,008	2,757	0.9	15.2	1.2	1295.0	14	36.8	13	53.1 (32.7)	12	37.3 (27.4)

Taxa	Type	Min Elev.	Max Elev.	Min Depth	Max Depth	Min Area	Max Area	Prevalence		Composition		Frequency	
								N_P	%P	N_C	%C	N_F	%F
Myriophyllum spicatum	S	335	2,664	1.8	25.0	4.5	1092.7	10	26.3	9	55.8 (34.5)	5	39.6 (26.5)
Najas guadalupensis	S	1,567	1,567	15.2	15.2	8.1	8.1	1	2.6	1	3.6	1	3.0
Najas marina	S	23	1,567	1.8	27.4	4.0	1214.1	8	21.1	8	56.6 (42.5)	6	46.9 (26.1)
Nitella spp.	S	977	1,642	4.6	25.0	4.0	50.6	2	5.3	2	11.8 (13.7)	1	17.0
Phragmites australis	E	23	583	2.4	73.2	131.5	1039.3	3	7.9	3	16.4 (17.2)	2	3.5 (0.7)
Polygonum amphibium	E	1,488	2,403	0.9	15.2	4.0	1295.0	13	34.2	10	11.6 (10.0)	10	8.9 (7.0)
Polygonum argyrocoleon	E	1,685	1,685	12.2	12.2	22.3	22.3	1	2.6	1	2.2	0	.
Polygonum lapathifolium	E	1,168	2,143	12.2	25.0	18.2	105.2	4	10.5	0	.	0	.
Polygonum spp.	E	55	583	3.0	73.2	259.0	1039.3	2	5.3	1	2.8	0	.
Pontederia spp.	E	2,044	2,044	1.8	1.8	32.4	32.4	1	2.6	1	7.1	1	7.0
Potamogeton crispus	S	23	1,700	1.8	2.4	2.0	131.5	2	5.3	1	86.5	1	64.0
Potamogeton foliosus	S	1,567	1,567	15.2	15.2	8.1	8.1	1	2.6	1	1.2	1	1.0
Potamogeton pusillus	S	23	2,664	1.8	19.8	1.2	1295.0	10	26.3	9	19.7 (26.1)	8	16.9 (21.4)
Rannunculus longirostris	S	2,168	2,664	0.9	13.7	1.2	30.4	5	13.2	5	5.4 (3.3)	5	4.4 (2.6)
Rorippa nasturtium-aquaticum	E	2,117	2,117	0.9	0.9	0.4	0.4	1	2.6	1	11.1	1	10.0
Schoenoplectus acutus	E	23	2,664	0.9	25.0	2.0	1214.1	17	44.7	13	9.8 (10.4)	12	7.1 (8.9)
Scirpus microcarpus	E	2,664	2,664	13.7	13.7	4.5	4.5	1	2.6	0	.	0	.
Sparganium spp.	E	2,047	2,047	3.0	3.0	68.8	68.8	1	2.6	1	1.0	1	1.0
Spirodela polyrhiza	F	1,168	1,168	19.8	19.8	18.2	18.2	1	2.6	1	4.0	0	.
Stuckenia filiformis	S	951	951	6.1	6.1	13.0	13.0	1	2.6	1	2.0	1	1.0
Stuckenia pectinatus	S	23	2,757	0.9	15.2	4.0	1295.0	16	42.1	16	42.2 (29.1)	16	36.4 (28.6)
Typha spp.	E	23	2,259	1.2	73.2	2.0	1214.1	18	47.4	15	22.1 (27.2)	11	5.1 (4.1)
Veronica anagallis-aquatica	E	1,567	1,567	15.2	15.2	8.1	8.1	1	2.6	1	1.2	1	1.0

Eurasian watermilfoil was found at nine (24%) of the reservoirs we surveyed; curly-leafed pondweed was found at two (5%) of the reservoirs we surveyed, but at one of these reservoirs curly-leafed pondweed was not found on a transect but was seen floating at the boat ramp. Some of the plants in this study were not identified to species because of lack of identifying structures such as seeds or flowers. In four surveyed reservoirs, we detected no aquatic macrophytes in the water: Cataract Lake, Knoll Lake, Lake Pleasant, and Woods Canyon Lake (Woods Canyon Lake and Cataract Lake had emergent taxa along the bank).

A few of the aquatic macrophyte species dominated (percent compositions greater than 50%) the species assemblage at study reservoirs where they were found (Table 2). Curly-leafed pondweed, an invasive nonnative, dominated (87% composition) the assemblage at the one reservoir where it was found on transects. Eurasian watermilfoil, also an invasive nonnative, was the most dominant aquatic macrophyte at four of the eight reservoirs where it was found on transects and had a mean composition of 61% at these eight reservoirs. For native species, the most dominant species was spiny naiad, which was found on transects at eight reservoirs (mean composition of 57%) and was the dominant aquatic macrophyte at five of those reservoirs (> 75% composition). Spiny naiad was dense in backwater reservoirs along the Colorado River such as Martinez Lake near Yuma, Arizona and Topock Marsh near Kingman, Arizona. Northern watermilfoil was the next most dominant native species, being the most common plant at 8 of the 13 reservoirs where it was found, with a mean composition of 54%. Several other native species that tended to dominate the aquatic plant communities included coontail (dominated at 5 of 16 reservoirs where it was present and had a mean percent composition of 48%), two-leaf elodea (dominated at 3 of 11 reservoirs where it was present and had a mean percent composition of 44%), and sago pondweed (dominated at 5 of 16 reservoirs where it was present and had a mean percent composition of 42%). Several taxa mentioned above were especially abundant with percent compositions in excess of 90% at nine reservoirs: coontail, spiny naiad, sago pondweed, northern watermilfoil, Eurasian watermilfoil, and filamentous algae.

We detected 20 significant ($p < 0.05$) positive associations (co-occurrence) between pairs of aquatic plant taxa (Table 3). For taxa groupings with more than two species, the most common aquatic plant assemblage in Arizona reservoirs was comprised of two-leaf elodea, water knotweed, and coontail; this assemblage was found at ten reservoirs. An assemblage comprised of these three species plus sago pondweed was found at six reservoirs. Other groupings of more than two taxa were less common. We also detected two negative associations (Table 3): cattail with creeping spikerush (*Eleocharis palustris*), and Eurasian watermilfoil with muskgrass.

Results of logistic regressions indicate that average depth and elevation were significant predictors of species occurrence (Appendix A2). Average depth was a significant predictor of occurrence for two species: water knotweed and sago pondweed. Both were more likely to be found in reservoirs that were shallow than those that were deep. Average depth was not a significant predictor of occurrence for other species examined. Elevation was a significant predictor of species occurrence for six

Table 3. Co-occurrence (phi coefficient: Zar 1984) of aquatic plant taxa found in Arizona reservoirs during surveys 2004 through 2006. Significant (P < 0.05) phi coefficients are indicated with an asterisk; N = 38 reservoirs. Coefficients with water buttercup, and hard-stem bulrush were not significant and are not shown.

		Coontail	Muskgrass	Two-leaf elodea	Creeping spikerush	Filamentous algae	Northern watermilfoil	Eurasian watermilfoil	Spiny naiad	Water knotweed	Small pondweed	Sago pondweed
Muskgrass	Φ_2	0.275										
	P	0.094										
Two-leaf elodea	Φ_2	0.513	0.141									
	P	0.001*	0.400									
Creeping spikerush	Φ_2	0.213	0.102	0.382								
	P	0.198	0.542	0.018*								
Filamentous algae	Φ_2	0.350	0.339	0.356	0.288							
	P	0.031*	0.037*	0.028*	0.080							
Northern watermilfoil	Φ_2	0.233	0.178	0.355	0.141	0.297						
	P	0.160	0.284	0.029*	0.399	0.070						
Eurasian watermilfoil	Φ_2	0.152	-0.339	0.054	0.016	0.019	-0.297					
	P	0.363	0.037*	0.748	0.924	0.909	0.070					
Spiny naiad	Φ_2	-0.048	0.361	-0.187	-0.108	-0.168	-0.261	-0.136				
	P	0.774	0.026*	0.260	0.517	0.314	0.114	0.416				
Water knotweed	Φ_2	0.621	0.240	0.763	0.444	0.271	0.484	0.120	-0.236			
	P	0.000*	0.147	0.000*	0.005*	0.100	0.002*	0.472	0.153			
Small pondweed	Φ_2	0.096	0.208	0.014	0.131	0.333	0.163	0.089	-0.015	-0.053		
	P	0.568	0.210	0.934	0.433	0.041*	0.328	0.596	0.927	0.752		
Sago pondweed	Φ_2	0.352	0.382	0.513	0.344	0.350	0.343	-0.224	0.344	0.509	-0.147	
	P	0.030*	0.018*	0.001*	0.034*	0.031*	0.035*	0.176	0.034*	0.001*	0.380	
Cattail	Φ_2	-0.169	-0.050	-0.257	-0.361	-0.215	-0.178	-0.157	0.286	-0.240	0.031	-0.062
	P	0.312	0.766	0.119	0.026*	0.194	0.284	0.348	0.082	0.147	0.851	0.712

species. Cattails and spiny naiad were more likely to occur at low elevation reservoirs than at high elevation reservoirs, whereas two-leaf elodea, northern watermilfoil, water knotweed, and water buttercup (*Rannunculus longirostris*) were more likely to occur at high elevation reservoirs than at low elevation reservoirs. Eurasian watermilfoil, coontail, small pondweed, creeping spikerush, and hard-stem bulrush occurred at broader ranges of elevations; therefore elevation was not a significant predictor of occurrence for these species. Average surface area was not a significant predictor of occurrence for any single species examined. Average surface area (log transformed) was however, significantly related to the number (log transformed) of submersed aquatic plant taxa found at reservoirs [log species = 0.386 + 0.117(log area), $r^2 = 0.151$, df = 1, 24, $p = 0.05$]; no relationships between surface area and number of emergent species or total species were statistically significant.

Reservoirs where aquatic vegetation was harvested tended to have several species in common. For example, half (nine) of the harvested reservoirs that were surveyed for aquatic plants had Eurasian watermilfoil present. Interestingly, 9 of the 10 reservoirs with Eurasian watermilfoil present were harvested, suggesting that harvesting operations have spread this plant among reservoirs. Filamentous alga was found in all 17 of the harvested reservoirs that we surveyed, but was also found at 10 of the reservoirs that were not harvested. Several other species common in harvested reservoirs were also common in non-harvested reservoirs: two-leaf elodea (in eight harvested and eight non-harvested reservoirs), coontail (in 10 harvested and 6 non-harvested reservoirs), muskgrass (in 7 harvested and 13 non-harvested reservoirs), and northern watermilfoil (in six harvested and eight non-harvested reservoirs).

EVALUATION OF HARVESTING PROGRAM

Aquatic Vegetation Coverage

A decrease in estimated percent aquatic plant coverage from immediately before harvesting to after immediately harvesting was evident for six harvesting events (Figure 4). Estimated vegetation coverage decreased from 74% immediately before to 49% immediately after harvesting at Luna Lake during 2005, from 73 to 67% at Luna Lake during 2006, from 27 to 3% at Parker Canyon Lake during 2006, from 40 to 38% at Crescent Lake during 2005, from 60 to 41% at Cluff Pond #3 during 2006, and from 53 to 30% at Rainbow Lake during 2006. Estimated vegetation coverage increased from immediately before to immediately after harvesting at Parker Canyon during 2005 (from 18 to 20%), and at Pena Blanca Lake during spring 2005 (22 to 28%). During 2006, the decreases in aquatic macrophyte cover at each lake during or immediately following the harvesting period was partly due to increases in lake depth because of precipitation and runoff. For example, we estimated that lake levels increased approximately 2 m at Parker Canyon Lake, 1 m at Luna Lake, 1 m at Cluff Pond #3, and 2 m at Rainbow Lake. The change in lake levels not only decreased macrophyte surface cover, but also reduced the efficiency of the harvesters because the operators harvest where they can see macrophytes on or near the water surface and the machines have a maximum cutting depth of 1.68 meters.

In the reservoirs that we monitored water chemistry and aquatic plant coverage, harvesters removed: 70 and 247.5 tons from Pena Blanca Lake during 2005, 12.5 tons from Crescent Lake during 2005, 160 and 50

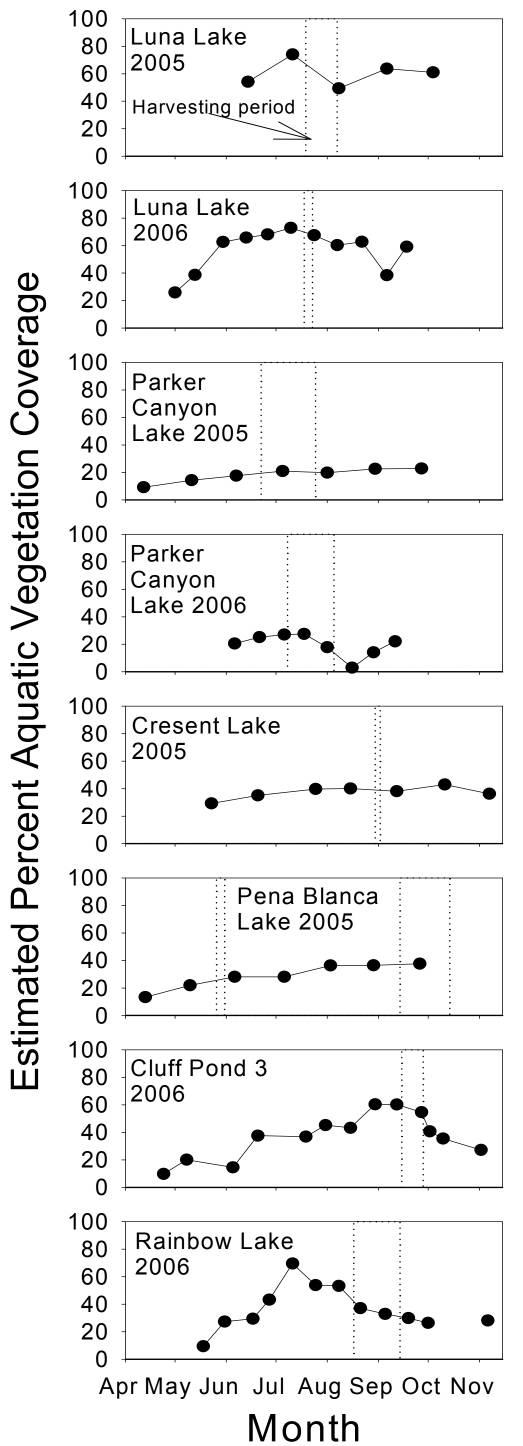

Figure 4. Monthly (2005) and bi-monthly (2006) estimates of percent aquatic macrophytes coverage (derived from GPS routes along edge of macrophytes beds) at each lake monitored during 2005 and 2006. Dotted vertical lines represent the period during which aquatic plant harvesting occurred.

tons from Parker Canyon Lake during 2005 and 2006 respectively, 756 and 336 tons from Luna Lake during 2005 and 2006 respectively, 9 tons from Cluff Pond during 2006, and 28 tons from Rainbow Lake during 2006.

Fish Kills

For all reservoirs monitored, we observed few dead fish during the aquatic vegetation coverage surveys (Figure 5). A pairwise t-test comparing the average number of dead fish observed per survey before versus after harvesting at the eight reservoirs was insignificant (before = 1.44 dead fish, after = 0.88 dead fish, $t = 0.74$, $df = 7$, $p = 0.459$), likely because most observations were of zero dead fish observed. Based on an examination of the graphs it appears that on average, more dead fish were observed before harvesting than after harvesting at five reservoirs: Luna Lake and Crescent Lake during 2005 and Rainbow Lake, Cluff Pond #3, and Parker Canyon Lake during 2006; the difference is slight at Parker Canyon Lake during 2006, but number of dead fish observed declined through the harvesting period but spiked afterward. At Parker Canyon Lake during 2005 and Luna Lake during 2006 fewer, on average, dead fish were observed before than after harvesting. No clear pattern was evident for Pena Blanca Lake during 2005.

Water Chemistry

We had hypothesized that water quality measures from treatment (harvested) and control (not harvested) locations would be similar before harvesting and then would diverge subsequent to harvesting. Based on examination of graphs (Figures 6-13) and ARIMA trend analyses, water quality measures for treatment and control locations were similar during the pre-treatment period, or if different, then usually trended in the same direction. However, divergence in

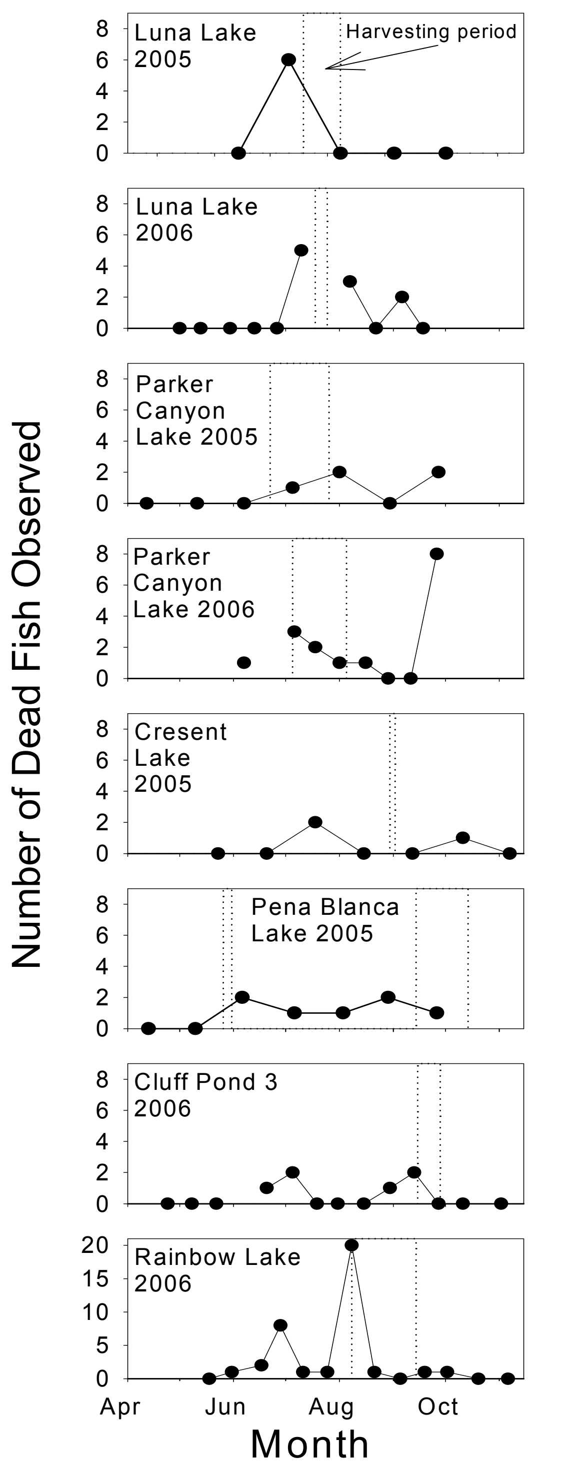

Figure 5. Number of dead fish observed during aquatic vegetation coverage sampling at each lake monitored during 2005 and 2006. Dotted vertical lines represent the period during which aquatic plant harvesting occurred. Note y-axis scales are not all the same.

water quality measures between treatment and control locations in the post-harvesting period were not evident; that is, the harvesting event was not a significant ($p > 0.05$) intervention in any ARIMA model. For example, levels of pH for both the mid-day sampling (Figure 6) and 22-hour sonde sampling (Figure 7a) were very similar in treatment and control locations after harvesting. Dissolved oxygen concentrations for both the 22-h sonde sampling (Figure 7b) and the mid-day (Figure 8) sampling also were very similar in treatment and control locations following harvesting, except in Luna Lake and Crescent Lake during 2005 (Figure 8) where concentrations increased in the treatment coves immediately following harvesting and decreased in the control coves, and 22-hour sonde dissolved oxygen concentrations from Luna Lake during 2006 (Figure 7b) were different between control and treatment coves both before and after harvesting with no clear pattern that would indicate the difference was a result of harvesting. Nitrate and orthophosphate concentrations (Figure 9) for mid-day sampling were similar in treatment and control coves prior to and after harvesting, or if they diverged, then no pattern was evident. Harvesting also did not appear to have an affect on chlorophyll *a* concentrations (Figure 10), alkalinity (Figure 11), water temperature (Figure 12) or turbidity (Figure 13).

We evaluated potential relationships between planktonic algae and water quality variables with Parson's correlation coefficient (Zar 1984); we ran correlations between chlorophyll *a* concentrations and pH, water temperature, turbidity, and concentrations of dissolved oxygen, alkalinity, orthophosphates and nitrates for each reservoir monitored each year. At most lakes, correlations were not significant ($p > 0.05$). Chlorophyll *a* concentrations were

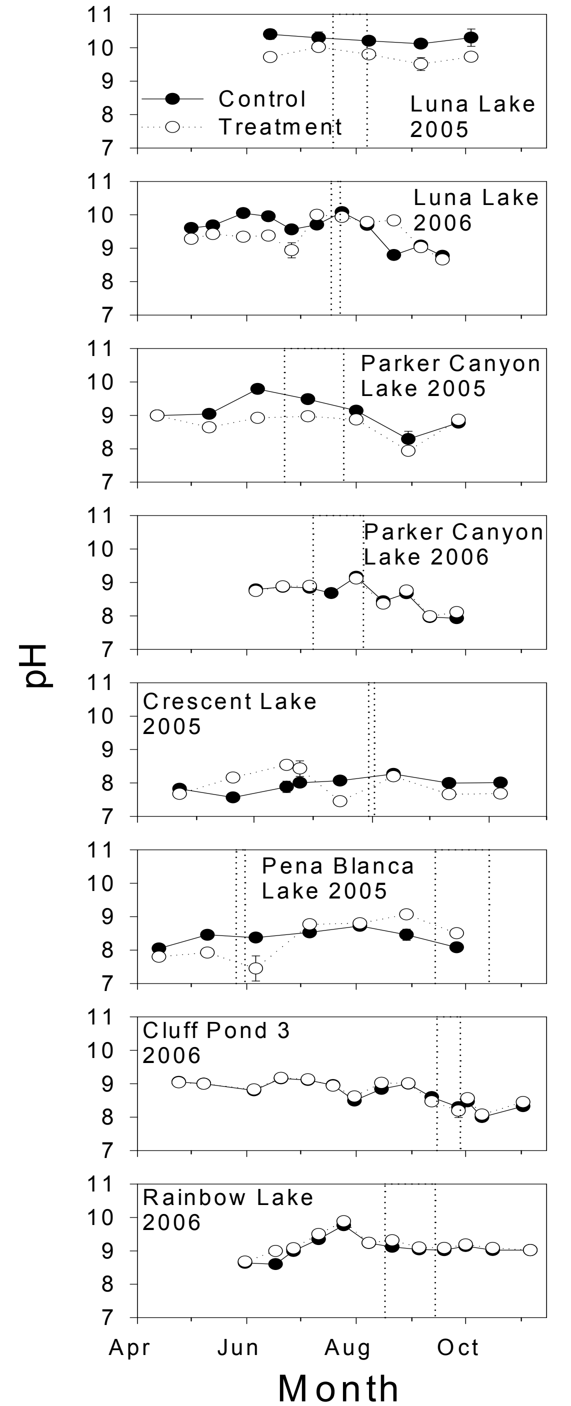

Figure 6. Mean, with standard error bars, monthly (2005) and bi-monthly (2006) mid-day pH of three measurements from the treatment (harvested) and control (not harvested) transects at each lake monitored during 2005 and 2006. Dotted vertical lines represent the starting and ending dates during which aquatic plants were harvested.

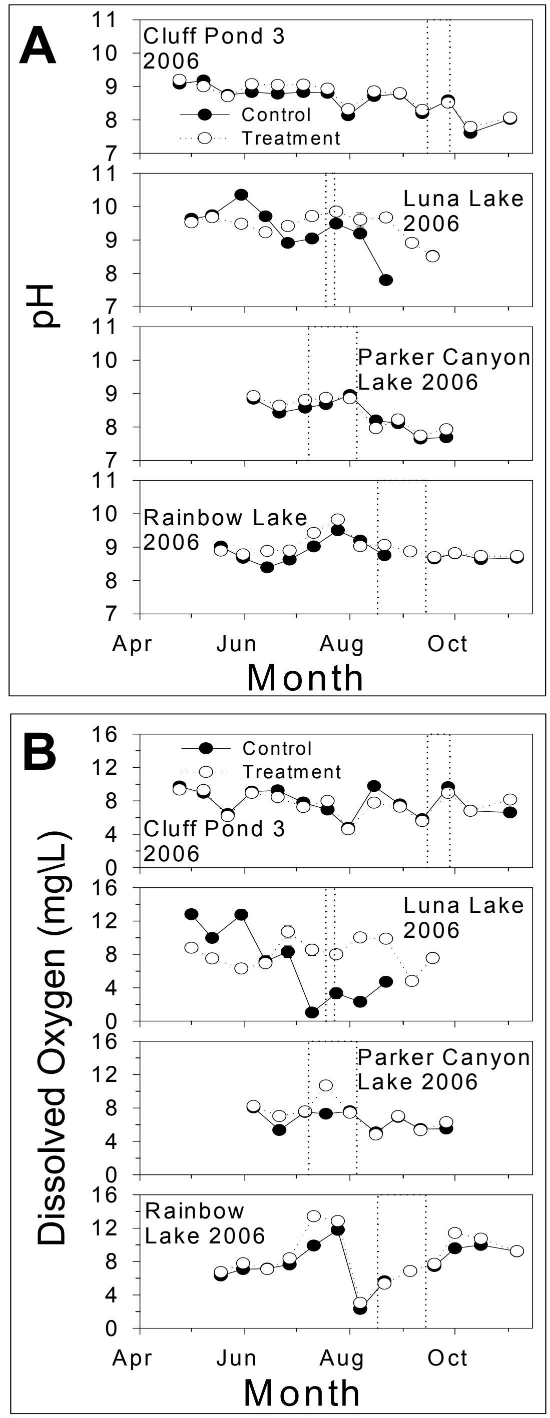

Figure 7. Mean, with standard error bars, daily (A) pH and (B) dissolved oxygen concentration measured every 2 h for 22 h at bi-weekly intervals within treatment (harvested) and control (not harvested) coves at four reservoirs during 2006. Dotted vertical lines represent the period during which aquatic plant harvesting occurred.

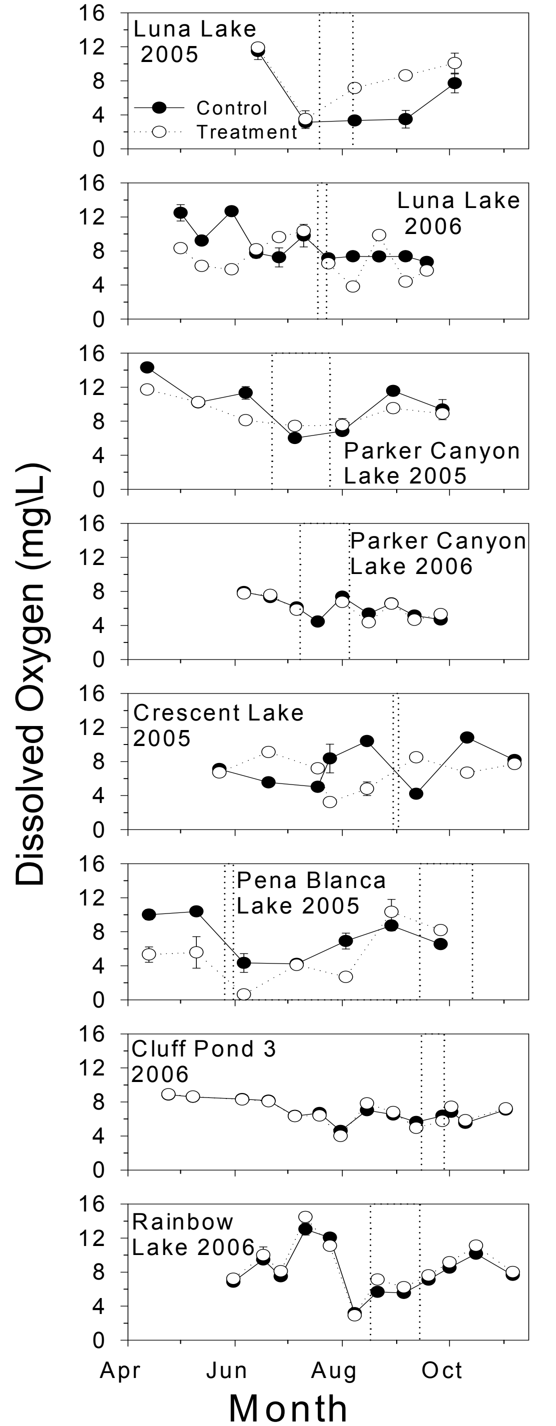

Figure 8. Mean, with standard error bars, monthly (2005) and bi-monthly (2006) mid-day dissolved oxygen concentration (mg/L) of three measurements on the treatment (harvested) and control (not harvested) transects at each lake monitored during 2005 and 2006. Dotted vertical lines represent the period during which aquatic plants were harvested.

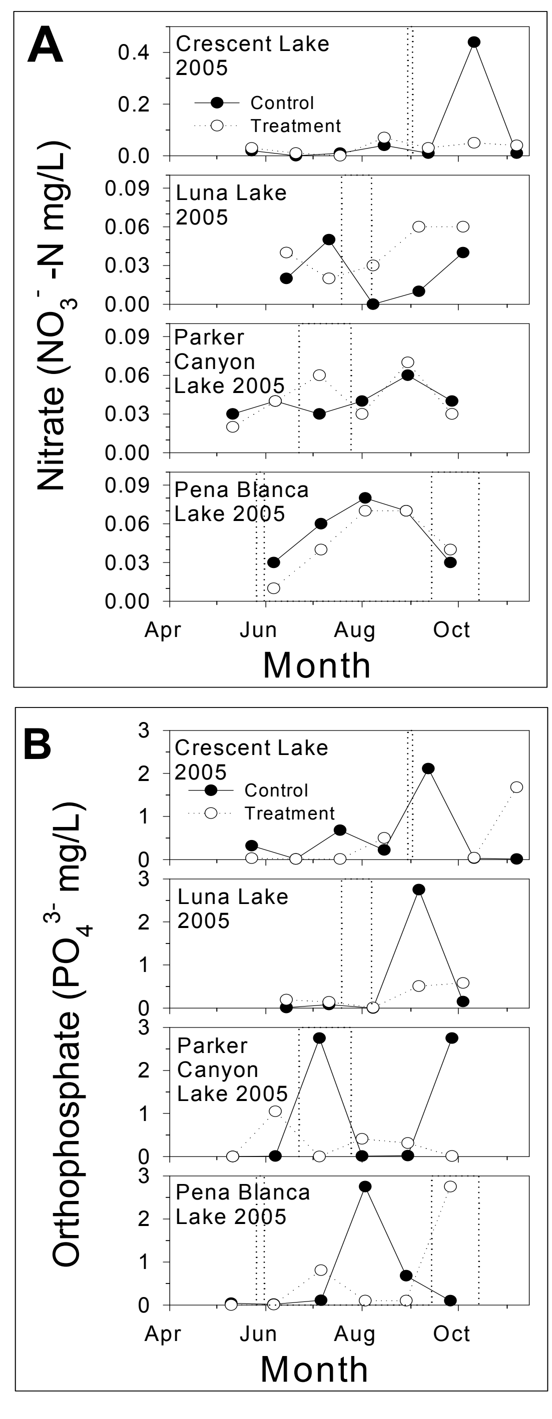

Figure 9. Monthly mid-day nitrate (A) and orthophosphate (B) concentrations (mg/L) of three-part composite samples from the treatment (harvested) and control (not harvested) transects at four reservoirs during 2005. Dotted vertical lines represent the period during which aquatic plants were harvested. Note y-axis scales are not all the same.

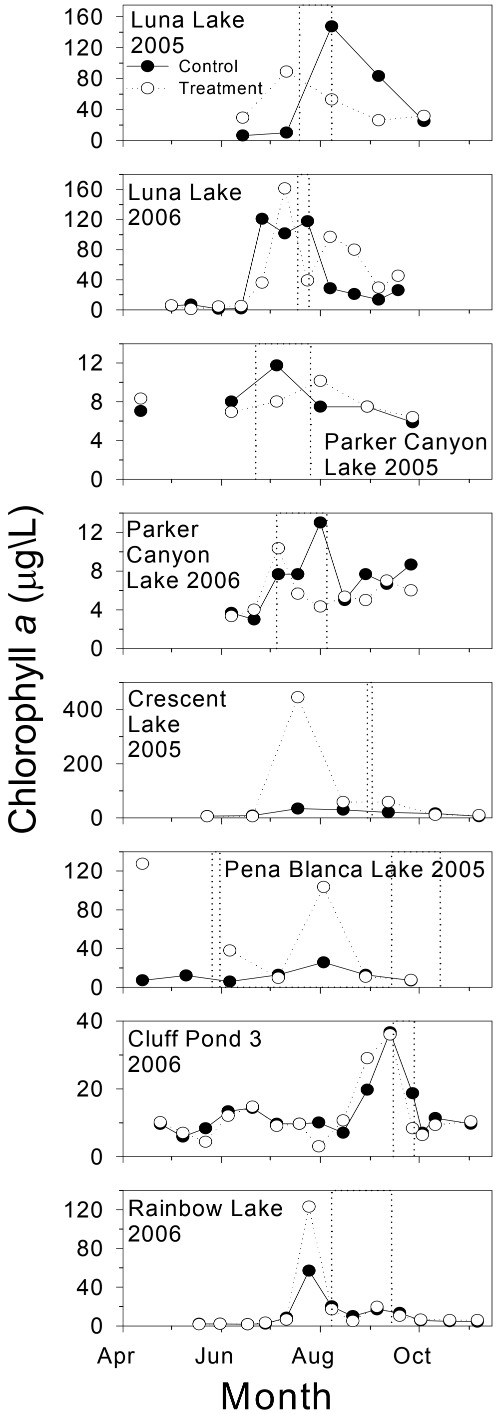

Figure 10. Monthly (2005) and bi-monthly (2006) mid-day chlorophyll a concentrations of three-part composite samples from treatment (harvested) and control (not harvested) transects at each lake monitored during 2005 and 2006. Dotted vertical lines represent the period during which aquatic plants were harvested. Note y-axis scales are not all the same.

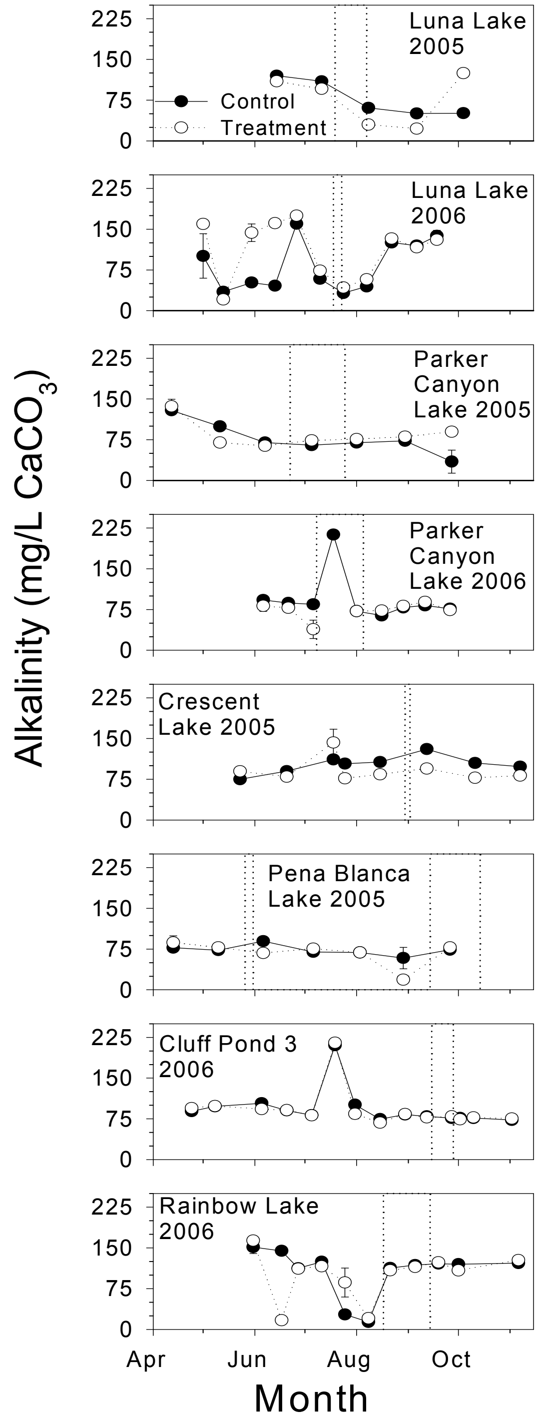

Figure 11. Monthly (2005) and bi-monthly (2006) mid-day mean, with standard error bars, alkalinity of three measurements from the treatment (harvested) and control (not harvested) transects at each lake monitored during 2005 and 2006. Dotted vertical lines represent the period during which aquatic plants were harvested.

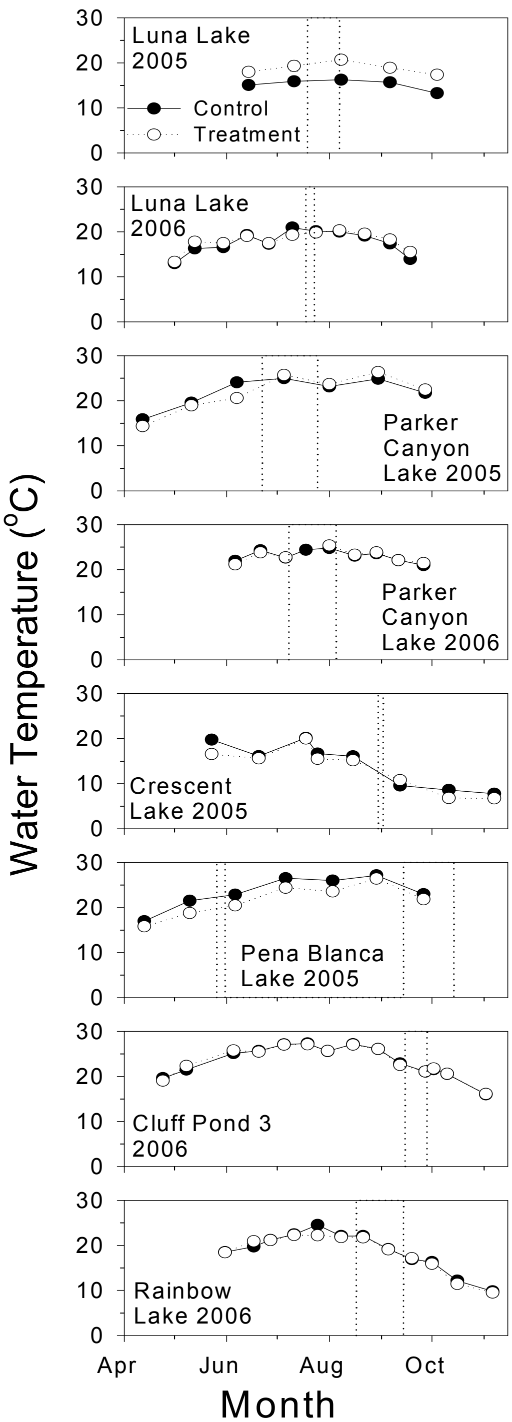

Figure 12. Monthly (2005) and bi-monthly (2006) mid-day mean, with standard error bars, water temperature of three measurements from the treatment (harvested) and control (not harvested) transects at each lake monitored during 2005 and 2006. Dotted vertical lines represent the period during which aquatic plants were harvested.

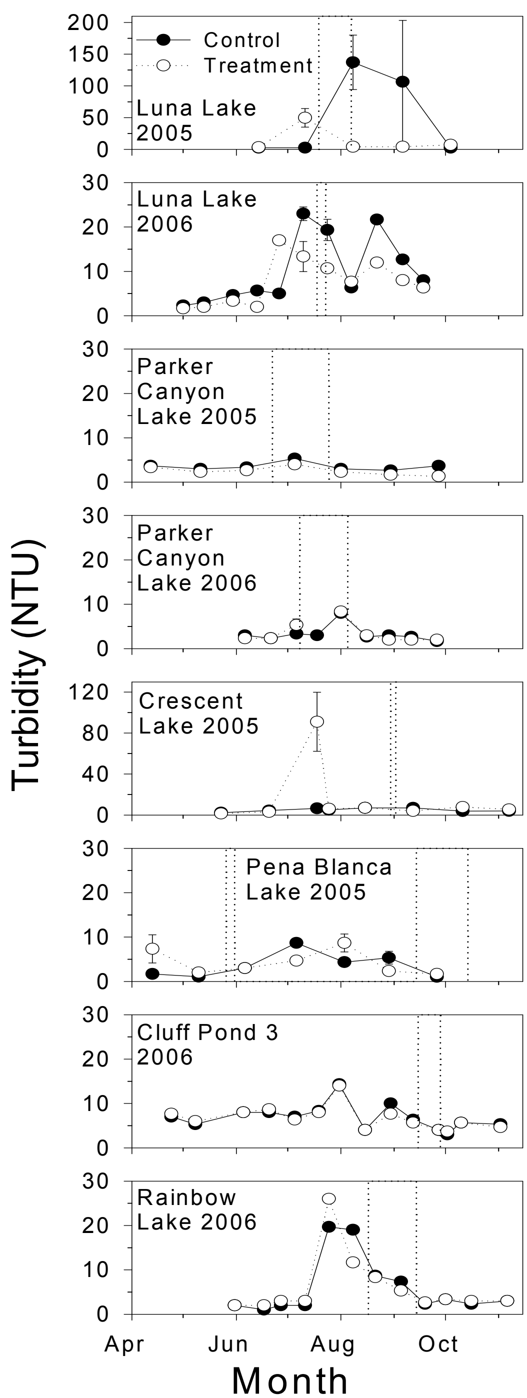

Figure 13. Monthly (2005) and bi-monthly (2006) mid-day mean, with standard error bars, turbidity of three measurements on the treatment (harvested) and control (not harvested) transects at each lake monitored during 2005 and 2006. Dotted vertical lines represent the period during which aquatic plants were harvested. Note, y-axis scales are not all the same.

positively correlated with turbidity at Pena Blanca Lake (*r* = 0.721, N = 13, *p* = 0.003), Rainbow Lake (*r* = 0.847, N = 39, *p* < 0.001)), Luna Lake during 2005 (*r* = 0.936, N = 10, *p* < 0.001), Luna Lake during 2006 (*r* = 0.649, N = 33, *p* < 0.001), and Parker Canyon Lake during 2006 (*r* = 0.554, N = 33, *p* = 0.003). At Rainbow Lake there were also significant correlations between chlorophyll *a* concentrations and water temperature (*r* = 0.343, N = 39, *p* = 0.033), percent saturation dissolved oxygen (*r* = 0.335, N = 36, *p* = 0.046), and pH (*r* = 0.655, N = 39, *p* < 0.001), and at Luna Lake during 2006 there was a positive correlation between chlorophyll *a* concentration and water temperature (*r* = 0.498, N = 33, *p* = 0.003).

Operational Cost of Harvesting

Tons of aquatic plants harvested was positively associated with duration the harvester was operated (*r* = 0.661, N = 161, *P* < 0.001) and with total cost (*r* = 0.686, N = 163, *P* < 0.001). Duration that the harvester was operated was also positively associated with total cost (*r* = 0.756, N = 238, *P* < 0.001). We did not detect any consistent downward trends from year to year in tons of aquatic plants harvested (Figure 14). The Aquatic Weed Harvesting Program expended approximately 1.3 million dollars from its inception in 1982 through 2006 (Figure 15; an average of $50,601 per year); this amount does not include the cost of the harvesters. Adding in the purchase cost of the harvesters brings the total to approximately 1.49 million dollars; the H-650 cost ~$60,000, the H-620 cost $103,500, and the HM-220 cost $62,000.

Incidental Fish Collection

Five fish species (two additional types not fully identified) were found in our samples (wheel barrel loads) of harvested weeds at the five reservoirs examined (Table 4). All

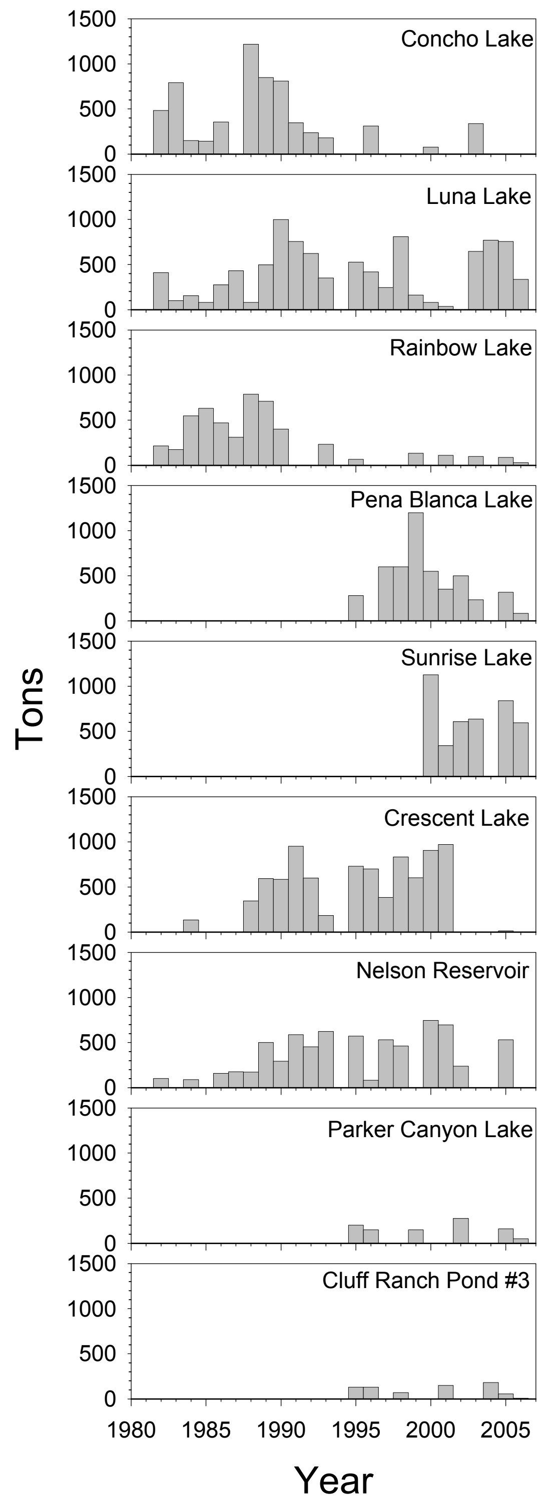

Figure 14. Estimated tons (wet weight) of aquatic vegetation harvested each year in nine Arizona reservoirs; 18 other reservoirs that were harvested in fewer than 6 years or without estimates of tons harvested are not shown.

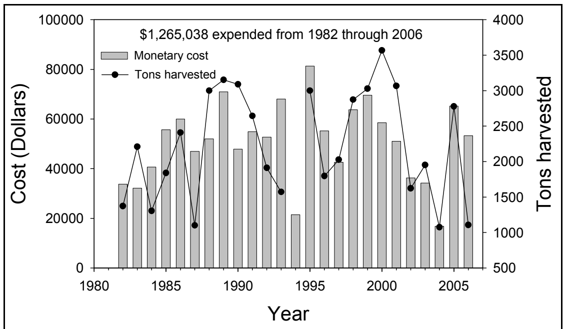

Figure 15. Total cost (bars) of the Aquatic Weed Harvesting Program and tons (wet weight, solid black line) harvested per year from 1982 through 2006.

but one of the species, fathead minnow, were sport fish. The ten unknown fish at Pena Blanca Lake were originally identified as trout because of observed dark vertical bands (these fish were inadvertently not collected and preserved), but given their size (all < 30 mm TL) and month (May 27, 2005) captured, they may also have been black crappie or sunfish. Fingerling trout were stocked on March 15, so they should have grown larger than 30 mm by May 27. The sample for the one other unknown fish from Parker Canyon Lake was lost, and no description was written down. For all reservoirs and samples, all fish found were less than 101 mm TL, and 87% were less than 50 mm TL.

Estimated number of fish entrapped in aquatic weeds per harvester load ranged from 57 (Rainbow Lake) to 818 (Cluff Pond) for the smaller HM-220 harvester, and 115 for the larger H-620 harvester used at Luna Lake (Figure 16). Estimated cost of fish per load ranged from $12 (Parker Canyon Lake) to $138 (Cluff Pond) for the smaller HM-220 harvester, and $9 for the larger H-620 harvester used at Luna Lake. The estimated total cost of fish harvested at each lake, calculated by multiplying the estimated cost per load times the number of loads harvested at each lake, was: $1,384 at Cluff Pond, $516 at Luna Lake, $577 at Parker Canyon Lake, $600 at Pena Blanca Lake, and $471 at Rainbow Lake.

Table 4. Numbers of fish per 1 m^3 sample of harvested aquatic weeds at five Arizona reservoirs during 2005 (Pena Blanca Lake) and 2006 (all other reservoirs).

	Lake				
Fish species	**Cluff Pond**	**Luna**	**Parker Canyon**	**Pena Blanca**	**Rainbow**
Ameiurus melas	0	0	0	0	4
Lepomis macrochirus	99	0	0	8	1
Lepomis spp.	0	0	8	0	0
Micropterus salmoides	0	0	0	0	2
Pimephales promelas	0	5	1	0	0
Pomoxis nigromaculatus	1	0	0	0	0
Unknown	0	0	1	10	0
Total	100	5	9	18	7

Angler Use Survey

The majority of anglers at all reservoirs (76%), and at each lake surveyed, thought that aquatic vegetation hindered them from fishing (Figure 17a). Half of the anglers

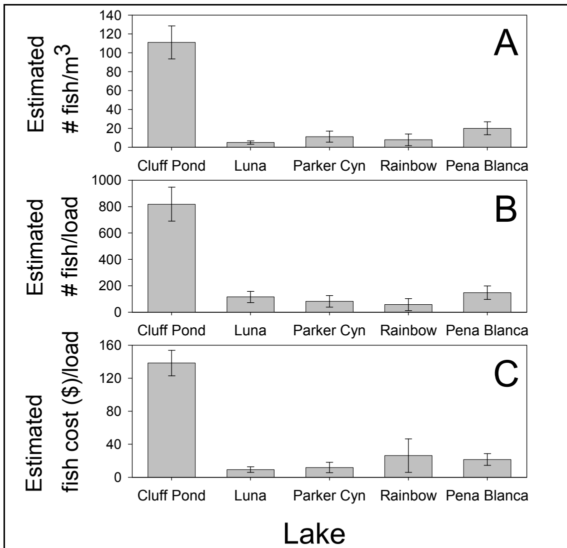

Figure 16. Estimated mean, and standard error, of (A) number of fish incidentally harvested per m^3, (B) number of fish incidentally harvested per load, and (C) cost of fish incidentally harvested per load from five Arizona Reservoirs in 2005 (Pena Blanca Lake) and 2006 (all other reservoirs shown). An Aquarius Systems H-620 aquatic weed harvester was used on Luna Lake and can hold 23.5 m^3 of plant material per load, whereas an Aquarius Systems HM-220 aquatic weed harvester was used on the other reservoirs and can hold 7.36 m^3 of plant material per load.

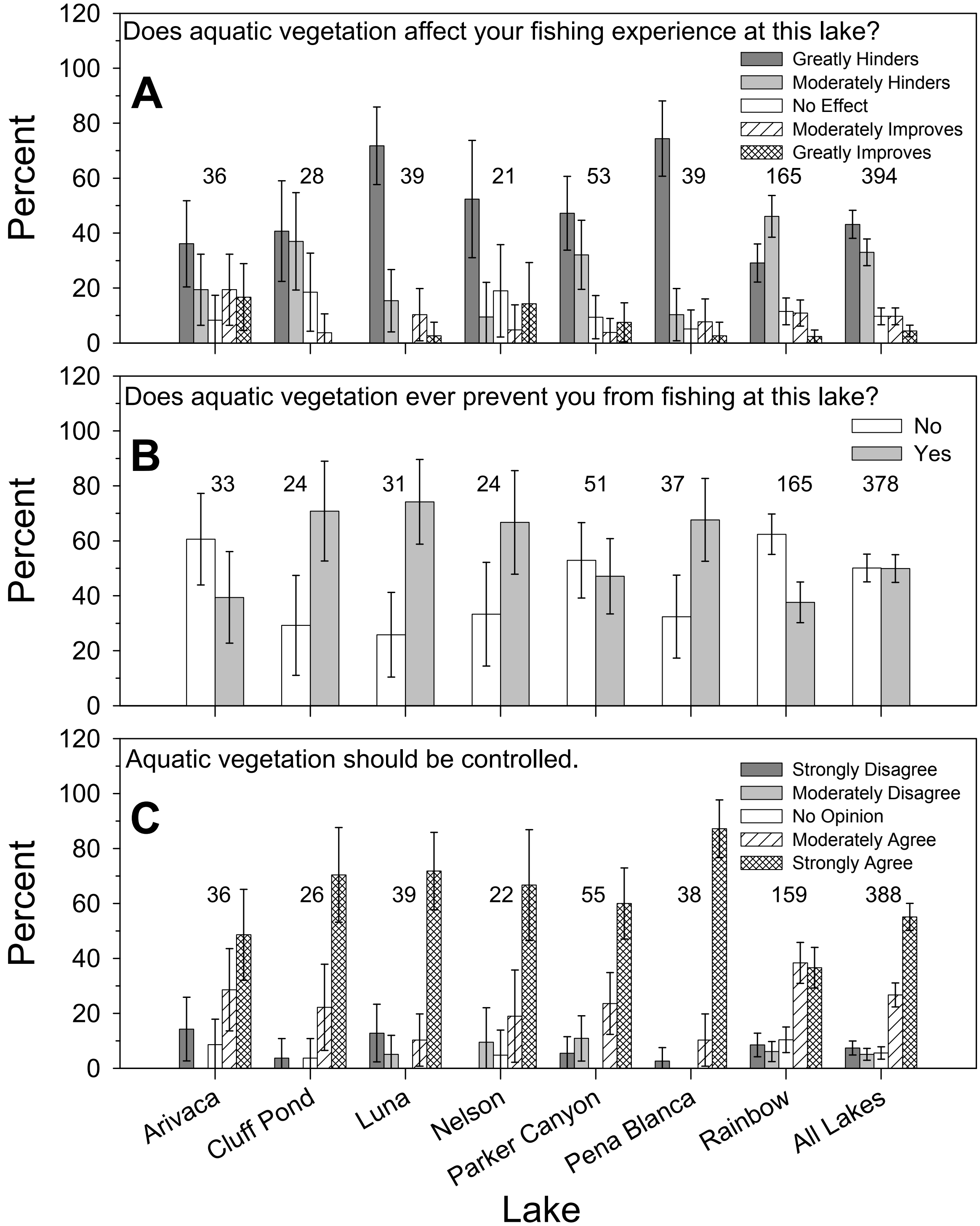

Figure 17. Percent of anglers, with 95% confidence intervals, that gave each response to question 1 (A: Does vegetation affect you fishing experience at this lake?), question 2 (B: Does vegetation ever prevent you from fishing at this lake?), and statement 3 (C: Aquatic vegetation should be controlled.). Numbers above each group of bars represents the number of anglers that responded at each lake.

surveyed indicated that aquatic vegetation prevented them from fishing at the survey lake at least once, whereas the other half indicated that aquatic vegetation never prevented them from fishing at the lake (Figure 17b). At Cluff Pond #3, Luna Lake and Pena Blanca Lake most anglers indicated that aquatic vegetation prevented them from fishing at the lake, whereas at Rainbow and Arivaca lakes most anglers indicated that aquatic vegetation never prevented them from fishing at the lake. Parker Canyon Lake had approximately equal proportions of 'Yes' and 'No' respondents. The majority of anglers surveyed at all reservoirs combined (81.8%), and at each lake surveyed, thought that aquatic vegetation should be controlled (Figure 17c). However, only at Parker Canyon Lake and Rainbow Lake did angler's estimates of the percent of the lake that was inaccessible decrease following or during harvesting compared to the period before harvesting (Figure 18). At Luna Lake, angler assessment of percent of lake that was inaccessible did not change from before to after harvesting, and insufficient data were collected at Cluff Pond and Pena Blanca Lake to determine if angler assessments of percent of the lake that was inaccessible decreased after harvesting.

The number of days that an angler fished that reservoir each year was correlated with the responses to each of the questions (Table 5). The more days per year anglers fished, the more likely they were to respond that aquatic vegetation hindered their fishing experience, or prevented them from fishing, and the more likely they were to respond that aquatic vegetation should be controlled. In addition, as the number of days fished increased, so did the angler's assessment of how much of the lake was inaccessible because of aquatic vegetation coverage.

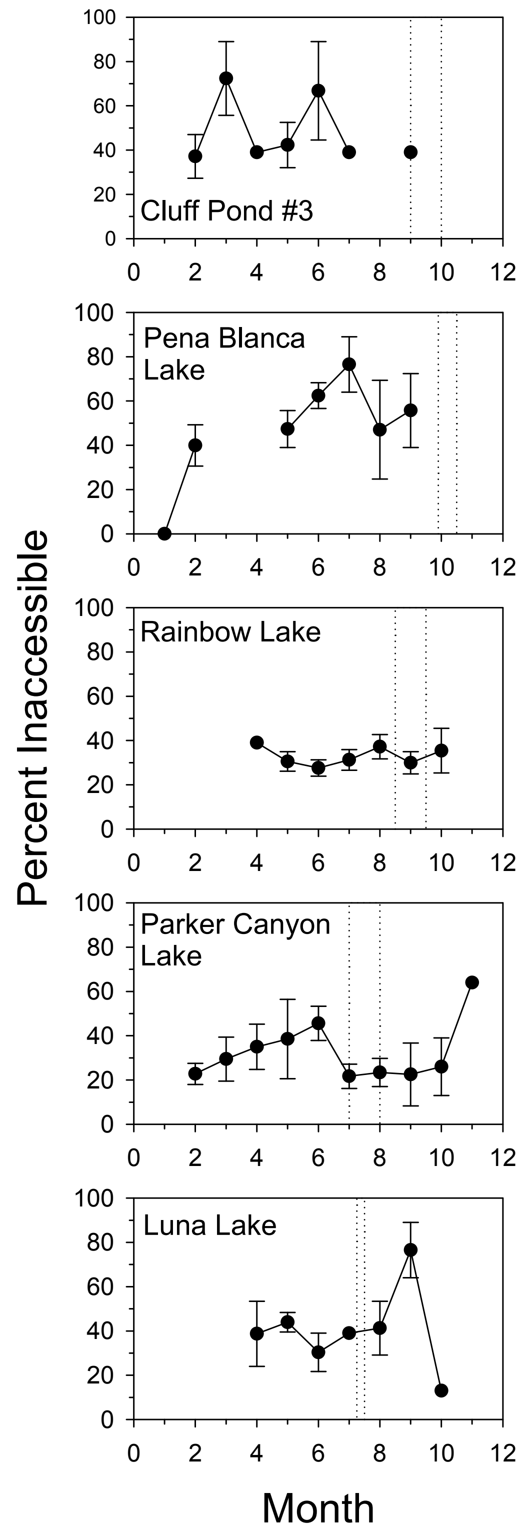

Figure 18. Angler assessments of the percentage, with 95% confidence intervals, of the lake that was inaccessible due to aquatic plants (i.e., estimate of percent aquatic plant coverage).

Table 5. Correlations among questions and days fished at the reservoir; *r* = Pearson's correlation coefficient, P = significance level, n = sample size.

		Question 1	Question 2	Question 3	Statement 4
Question 2	*r*	0.520			
	P	<0.001			
	n	374			
Question 3	*r*	-.481	-0.483		
	P	<0.001	<0.001		
	n	384	367		
Statement 4	*r*	-0.379	-0.357	0.227	
	P	<0.001	<0.001	<0.001	
	n	390	372	385	
Days fished at reservoir	*r*	-0.133	-0.321	0.182	0.163
	P	0.012	<0.001	0.001	0.002
	n	361	345	354	360

Anglers that thought that aquatic vegetation hindered their fishing or prevented them from fishing tended to think that aquatic vegetation should be controlled.

DISCUSSION

STATEWIDE AQUATIC PLANT SURVEY

Our data supports Santamaria (2002), that aquatic vascular plants generally have broad geographic ranges. Although many of the taxa sampled had broad distributions, it is important to note that elevation was a significant predictor of occurrence for several taxa. Two-leaf elodea, northern watermilfoil, water knotweed, and water buttercup were more likely to be found at higher than at lower elevations, whereas cattails and spiny naiad were more likely to be found at low elevation reservoirs. Eurasian watermilfoil, coontail, small pondweed, creeping spikerush, and hard-stem bulrush occurred at broader ranges of elevations and so elevation was not a significant predictor of occurrence for these species. Eurasian watermilfoil presence at reservoirs below 1,000 meters of elevation displays its ability to be an invasive at lower elevations where northern watermilfoil was not found. Monitoring of reservoirs where Eurasian watermilfoil is present will help us better understand its invasive ability and probability of spread in Arizona.

Average depth was also a significant predictor of occurrence for two species. Water knotweed and sago pondweed may be light-limited and so were more likely to be found in reservoirs that were shallow than those that were deep; average depth was not a significant predictor of occurrence for other species examined. Average surface area was not a significant predictor of occurrence for any of the species examined, but the number of species increased with increasing reservoir surface area, in support of island biogeography theory.

In most reservoirs, a single species did not form a continuous monoculture. Rather, our data indicate that most reservoirs had high densities of several taxa. The most common aquatic plant assemblage in Arizona reservoirs was comprised of two-leaf elodea, water knotweed, and coontail. Nineteen pairs of species tended to co-occur but there were four instances of negative co-occurrence. Negative species associations might result from competition, or other factors such as environmental requirements, dispersal vectors, or stochastic processes; experimental studies would be needed to confirm competition. Cattail and creeping spikerush were negatively associated with one another, and given that both are emergent species, it makes sense that they may compete. Eurasian watermilfoil was negatively associated with muskgrass, suggesting that it may compete with this species or environmental requirements of the two species may be different, or there may be other environmental conditions such as water quality and nutrient composition in specific reservoirs that may be causing this negative association.

Although results of other studies (Madsen et al. 1991, Boylen et al. 1999) have indicated that a decline in native vegetation can occur under dense Eurasian watermilfoil canopies, our data for the most part do not support this contention. Eurasian watermilfoil had greater percent composition than the cumulative percent composition of native plants at only three of the nine reservoirs where it occurred, and at only two reservoirs, Parker Canyon Lake and Goldwater Lake, was Eurasian watermilfoil the most dominant aquatic plant. Madsen (1998) found that reservoirs with more than 50% Eurasian watermilfoil dominance had less than 60% cumulative native plant coverage. Our data do not support this contention; at five of the nine reservoirs with Eurasian watermilfoil in our study, Eurasian watermilfoil had compositions greater than 50%, but of these five, four were shallow reservoirs for which we estimated percent coverage and only one had less than 60% cumulative native plant coverage. At the five reservoirs where native aquatic plants had higher percentage composition than Eurasian watermilfoil, it may be that time is needed for this macrophyte to increase coverage, native species in Arizona may out-compete this nonnative macrophyte, or that environmental requirements and dispersal vectors may be limiting this species success in Arizona. Nichols and Shaw (1986) reported that harvesting can encourage the spread of nuisance species because many species are able to propagate rapidly from plant fragments. It is likely that Eurasian watermilfoil has spread throughout Arizona reservoirs as a result of the Department's harvesting program, because nine of the ten reservoirs with Eurasian watermilfoil present were reservoirs that have been harvested.

Other studies have concluded that Eurasian watermilfoil could out-compete northern watermilfoil (Nichols 1994, but see Valley and Newman 1998 for an opposite conclusion) and spiny naiad (Agami and Waisel 1985). We did not detect a significant negative association in occurrence between the Eurasian watermilfoil and northern watermilfoil (Table 3), but at the one reservoir where the two species co-occurred (Goldwater Lake), Eurasian watermilfoil had a greater percent composition (87%) than northern watermilfoil (70%), lending some indirect support to the hypothesis that Eurasian watermilfoil is the superior competitor. Similarly, we did not detect a significant negative association between Eurasian watermilfoil and spiny naiad, but at Alamo Lake, the only reservoir where both species were present, spiny naiad comprised 12% of the species composition and Eurasian watermilfoil was 41%, lending indirect support to the findings of Agami and Waisel (1985).

We think that reservoir water levels, bathymetry, and substrate might explain the lack of aquatic macrophytes at four reservoirs. Unlike other reservoirs we examined, Lake Pleasant experiences large seasonal fluctuations in water level, which likely resulted in the absence of aquatic vegetation at this reservoir; U. S. Bureau of Reclamation pumps water into and stores water in the reservoir during winter and pumps water out into the Central Arizona Project canal during summer. Knoll Lake and Woods Canyon Lake were deep and had steep rocky sides and rocky substrates, so areas suitable for rooted aquatic vegetation were restricted to the few shallow stream inflow areas with fine substrates, which, for some unknown reason, were still absent of aquatic vegetation. Cataract Lake was not as deep as the other three reservoirs, but it still had mostly steep rocky sides and its bottom substrate was the same as the deeper reservoirs.

Filamentous algae and the native aquatic plants coontail, northern watermilfoil, sago pondweed, and spiny naiad, and the nonnative Eurasian watermilfoil had relatively high prevalence statewide (> 21%) and each had percent frequency of occurrence (an estimate of percent cover in our shallow reservoirs) in excess of 24%. These six taxa are, therefore, good targets for management. Muskgrass had a high prevalence but low percent frequency of occurrence within reservoirs, therefore, it is probably less of a management concern. Another species, curly-leafed pondweed, was listed as a problem by eight states because of its invasive and competitive abilities with other native aquatic plants (Bartodziej and Ludlow1997). This species may become problematic in Arizona, but, at present is not of widespread concern. Curly-leafed pondweed was only found at two reservoirs; it was rare at Mittry Lake, but at Granite Basin Lake it covered 64% of the reservoir with a composition of 87%.

Evaluation of Harvesting Program

Aquatic Vegetation Coverage, Fish Kills, and Water Chemistry

There were several climatic events that affected the outcome of our monitoring of harvested reservoirs. Lake levels were affected by drought and precipitation. The persistence of the drought, which began in 1996, caused water levels to decrease so low in several targeted reservoirs (Arivaca Lake and Nelson Reservoir) during 2006 that the harvesters could not be launched and hence the reservoirs could not be harvested. The list of potential alternatives was so short that two reservoirs that were harvested in the previous year (Parker Canyon Lake and Luna Lake) had to be chosen. The reservoirs that were monitored during 2006 all experienced increases in water levels, because of summer thunderstorms, during the period when they were harvested. The increase in water levels decreased the efficiency of harvesting because the harvesters can only cut to a depth of 1.5 m, and the lake levels increased by 1-2 m. In addition to affecting the efficiency of harvesting, the increased flow into the reservoir increased lake volume which may have affected water chemistry.

Another factor may have affected study results at Pena Blanca Lake. We consulted with the harvester crew and selected control and treatment coves in Pena Blanca Lake and began monitoring in April 2005. After the third sampling event, we found out that aquatic weeds harvested were dumped onshore-near shore at the back of our control cove; the US Forest Service would not grant permission to dump them on land because of mercury concerns. Therefore, the increase in plant matter may have affected water quality in the control cove.

We detected a decrease in aquatic vegetation cover following harvesting at most of the reservoirs we monitored. However, changes in water quality as a result of harvesting were not evident. Either harvesting had negligible effects on the variables we measured, our measurements were not sensitive enough to detect changes, or environmental events affected our results. We think that harvesting had negligible effects on water quality in the reservoirs we monitored. After examining the 2005 data, we did not see any clear changes in water chemistry variables as a result of harvesting. We wanted to rule out the possibility that mid-day readings were too variable to detect changes, if there were harvest-related changes. Therefore, during 2006, we deployed sondes for 22 hours at monitored reservoirs, but we still failed to detect changes in pH, water temperature or dissolved oxygen from before to after harvesting. Reservoir level increased during the harvesting period within each of the reservoirs that we monitored during 2006, which may have affected water quality, but the effect should have been similar in control and treatment areas. Even so, we did not detect divergence in water quality values between treatment and control locations. Therefore, our data indicate that harvesting did not have a detectable effect on water quality variables measured. In other words, we did not find evidence in support of two of our hypotheses relative to water chemistry; pH did not decrease and dissolved oxygen did not increase following harvesting. In addition, we did not detect a decrease in the numbers of dead fish observed from before to after harvesting, but given that we did not detect a change in dissolved oxygen concentrations, this is not surprising.

Effects of macrophytes on dissolved oxygen, pH, water temperature and chlorophyll concentrations tend to be localized (Wetzel 1983, Carter et al. 1991); levels are high in surface waters in macrophyte beds and low near the bottom. We measured dissolved oxygen, pH and water temperature at 1-m depth, so we might have detected increases in these variables if we had measured them at the surface. Regardless, if a reservoir has considerable unvegetated areas, it appears that phytoplankton will have more of a lake-wide effect on pH and dissolved oxygen than will aquatic macrophytes (Carter et al. 1991).

Macrophytes are most likely to affect water nutrient levels when they are senescing and plant matter is decomposing (Landers 1982). Harvesting aquatic vegetation has lowered phosphorus levels in lakes under certain conditions (Nichols 1991), but under most conditions, harvesting does not result in lower nutrient levels (Carpenter and Adams 1977). We did not detect changes in phosphorus or nitrate concentrations following harvesting. Most of our nutrient measurements were made prior to the senescence period (autumn); regardless we did not see consistent increases in nutrients in autumn among the four reservoirs monitored nor were nutrient concentrations greater in the control areas relative to the treatment areas during autumn. Therefore, we did not find evidence in support of our third hypothesis relative to water chemistry that nutrient levels after harvesting decreased in treatment areas relative to control areas.

Dissolved oxygen and nutrient concentrations and pH may have been more dependent upon phytoplankton, as effects of phytoplankton on these variables are well known (Wetzel 1983). However, we did not find significant correlations between mid-day chlorophyll *a* concentrations and dissolved oxygen or pH at most of the lakes monitored; Rainbow Lake was the exception. We also did not detect any divergence in phytoplankton at treatment and control locations, as measured by chlorophyll *a* concentrations, after harvesting, which supports published reports that mechanical control operations rarely cause algal bloom formation or other major changes in phytoplankton community structure (Wile and Hitchin 1977; Wile 1978; Engel 1990).

Operational Cost of Harvesting

The harvesting program expends approximately $50,600 per year to harvest an average of six reservoirs. This annual cost seems relatively small compared to the $250,000 - $300,000 annually spent mechanically harvesting approximately 1000 tons of aquatic weeds in Big Bear Lake, California (Frieman et al. 2004). We did not detect any consistent downward trends from year to year in tons of aquatic plants harvested, lending little support to the hypothesis that yearly harvesting depletes the nutrients in a lake and results in less plant biomass in successive years.

Incidental Fish

Harvesting can remove fish and invertebrates that are tangled in the vegetation (Wile 1978, Haller et al. 1980, Engel 1990). Our data indicate that relatively few fish were removed by harvesting aquatic plants. We found mostly young-of-year (YOY) gamefish, and a few small minnows in the samples of harvested aquatic plants that we examined. Over the course of harvesting a lake, several hundred fish are likely removed, but because they are YOY fish, the monetary value is not very great. In addition, most species of fish produce large amounts of young, and most of those young die within the first year of life. Therefore, from a population perspective, an individual YOY fish is expendable. Therefore, incidental fish removal as a result of harvesting aquatic vegetation is probably not of much concern in the reservoirs that we monitored.

Angler Survey

Wilde et al. (1992) reported that 22 to 35% of anglers supported aquatic vegetation removal in Texas. In contrast, we found that a super-majority (more than 75%) of anglers surveyed indicated that aquatic vegetation hindered their fishing experience, and should be controlled. In addition, the more days an angler fished per year the more they thought that aquatic vegetation should be controlled. Hence, anglers support the Department's efforts to control aquatic vegetation in problem reservoirs throughout the state. At two reservoirs, anglers estimation of percent of the lake that was inaccessible decreased immediately during or following harvesting, suggesting that the Department's aquatic weed harvesting program is increasing access for anglers for approximately a month following harvesting.

MANAGEMENT OPTIONS

Management of aquatic plants to improve access in Arizona's reservoirs should focus on filamentous algae, the non-native species Eurasian watermilfoil and curly-leafed pondweed, and the native species coontail, sago pondweed, spiny naiad, and northern watermilfoil. These species can cover extensive areas of reservoirs and form dense stands that hinder various recreational activities such as boating access, fishing, and swimming. Management of these species will inadvertently affect other plant species in the assemblage, particularly those that we found to co-occur with these species. The occurrence of the non-native invasive species Eurasian watermilfoil, curly-leafed pondweed, and others that have been recorded in the state during the past (e.g., giant salvinia, *Salvinia molesta*, and Hydrilla, *Hydrilla verticillata*) need to be monitored so that action can be taken to prevent their spread.

COST AND BENEFITS OF HARVESTING

Costs:

- Aquatic plant harvesting has likely resulted in the spread of the invasive Eurasian watermilfoil to reservoirs throughout Arizona.
- The aquatic plant harvesting program expends approximately $50,600 per year.
- Relatively few sport fish are removed by aquatic plant harvesting, and those that are removed tend to be expendable YOY fish.

Benefits:

- Harvesting immediately decreases aquatic vegetation cover and hence improves angler access.
- The majority of anglers are in favor of controlling aquatic vegetation.
- Harvesting is less contentious to the general public than using chemicals to control aquatic weeds.

Aquatic plant harvesting apparently does not change water chemistry enough to reduce fish kills or extend the trout stocking season. Based on the above mentioned costs and benefits, harvesting aquatic weeds is probably a worthwhile venture for the Department, especially because our angling customers want aquatic vegetation to be controlled. However, we suggest that more effective decontamination procedures for the harvesting machinery be implemented to limit the spread of invasive species. In addition, other techniques to control aquatic vegetation such as biological (grass carp) or chemical control should be considered on a case-by-case basis.

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For more detailed and technical presentations of methods, results and discussion of specific sections of this Technical Guidance Bulletin, the authors refer you to the following citations, which can be obtained by contacting:

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APPENDIX

Data Summary Tables

Table A1. Aquatic plant taxa found at each surveyed lake in Arizona, 2004-2006, and percent composition and percent frequency of each taxa. Definitions are as in Table 2.

Lake	No. points surveyed	No. points with plants	Taxa	No. points with taxa	% Composition	% Frequency
Alamo Lake	100	49	*Cyperus spp.*	25	51.0	
			Lemna minima	1	2.0	
			Myriophyllum spicatum	20	40.8	
			Najas marina	6	12.2	
Antelope Lake	100	88	*Chara spp.*	10	11.4	10.0
			Filamentous algae	10	11.4	10.0
			Myriophyllum sibiricum	76	86.4	76.0
			Potamogeton pusillus	60	68.2	60.0
			Rannunculus longirostris	3	3.4	3.0
Apache Lake	100	36	*Cyperus spp.*	1	2.8	
			Encrusting algae	2	5.6	
			Phragmites communis	13	36.1	
			Polygonum spp.	1	2.8	
			Typha spp.	25	69.4	
Arivaca Lake	100	88	*Ceratophyllum demersum*	84	95.5	
			Clinging algae	29	33.0	
			Filamentous algae	19	21.6	
			Planktonic alga bloom	2	2.3	
			Myriophyllum spicatum	34	38.6	
Becker Lake	100	56	*Ceratophyllum demersum*	3	5.4	3.0
			Chara spp.	17	30.4	17.0
			Filamentous algae	14	25.0	14.0
			Myriophyllum sibiricum	37	66.1	37.0
			Polygonum amphibium	5	8.9	5.0
			Schoenoplectnus acutus	4	7.1	4.0
			Stuckenia pectinata	21	37.5	21.0
Big Springs Pond	20	18	*Chara spp.*	10	55.6	50.0
			Eleocharis palustris	1	5.6	5.0
			Filamentous algae	12	66.7	60.0
			Rorippa nasturtium-aquaticum	2	11.1	10.0
			Unknown wetland plant	1	5.6	5.0
Cluff Pond #3	100	53	Filamentous algae	15	28.3	15.0
			Myriophyllum sibiricum	53	100.0	53.0
			Typha spp.	1	1.9	1.0
Concho Lake	100	93	*Ceratophyllum demersum*	53	57.0	53.0
			Eleocharis palustris	1	1.1	1.0
			Elodea bifoliata	11	11.8	11.0
			Filamentous algae	1	1.1	1.0
			Myriophyllum spicatum	3	3.2	3.0
			Polygonum amphibium	1	1.1	1.0
			Stuckenia pectinata	85	91.4	85.0
Crescent Lake	100	79	*Elodea bifoliata*	65	82.3	65.0

Lake	No. points surveyed	No. points with plants	Taxa	No. points with taxa	% Composition	% Frequency
			Filamentous algae	38	48.1	38.0
			Myriophyllum sibiricum	43	54.4	43.0
			Stuckenia pectinata	2	2.5	2.0
Dankworth Pond	100	79	*Chara spp.*	1	1.3	1.0
			Filamentous algae	54	68.4	54.0
			Najas marina	70	88.6	70.0
			Nitella spp.	17	21.5	17.0
			Stuckenia pectinata	22	27.8	22.0
			Typha spp.	12	15.2	12.0
			Unknown macrophyte 1	32	40.5	32.0
			Unknown macrophyte 2	1	1.3	1.0
			Unknown macrophyte 3	1	1.3	1.0
Ganado Lake	100	87	*Chara spp.*	2	2.3	2.0
			Eleocharis palustris	2	2.3	2.0
			Elodea bifoliata	62	71.3	62.0
			Filamentous algae	5	5.7	5.0
			Potamogeton pusillus	6	6.9	6.0
			Stuckenia pectinata	62	71.3	62.0
Goldwater Lake			*Myriophyllum sibiricum*	16	69.6	16.0
			Myriophyllum spicatum	20	87.0	20.0
Granite Basin Lake	100	74	*Eleocharis palustris*	2	2.7	2.0
			Filamentous algae	3	4.1	3.0
			Lemna minima	4	5.4	4.0
			Potamogeton crispus	64	86.5	64.0
			Potamogeton pusillus	1	1.4	1.0
			Schoenoplectnus acutus	1	1.4	1.0
			Typha spp.	11	14.9	11.0
Lower Lake Mary	100	50	*Ceratophyllum demersum*	33	66.0	33.0
			Chara spp.	1	2.0	1.0
			Elodea bifoliata	4	8.0	4.0
			Filamentous algae	1	2.0	1.0
			Polygonum amphibium	15	30.0	15.0
Luna Lake	100	80	*Carex spp.*	1	1.3	1.0
			Ceratophyllum demersum	33	41.3	33.0
			Eleocharis palustris	5	6.3	5.0
			Elodea bifoliata	50	62.5	50.0
			Filamentous algae	11	13.8	11.0
			Glyceria grandis	2	2.5	2.0
			Myriophyllum spicatum	62	77.5	62.0
			Polygonum amphibium	19	23.8	19.0
			Rannunculus longirostris	9	11.3	9.0
			Schoenoplectnus acutus	1	1.3	1.0
			Stuckenia pectinata	25	31.3	25.0

Lake	No. points surveyed	No. points with plants	Taxa	No. points with taxa	% Composition	% Frequency
Lynx Lake	100	45	*Cyperus esculentus*	1	2.2	
			Echinochloa crus-galli	3	6.7	
			Filamentous algae	1	2.2	
			Myriophyllum sibiricum	34	75.6	
			Myriophyllum spicatum	5	11.1	
			Polygonum argyrocoleon	1	2.2	
			Potamogeton pusillus	2	4.4	
			Typha spp.	2	4.4	
Marshall Lake	99	85	*Ceratophyllum demersum*	25	29.4	25.3
			Chara spp.	6	7.1	6.1
			Cyperus spp.	1	1.2	1.0
			Eleocharis palustris	1	1.2	1.0
			Elodea bifoliata	34	40.0	34.3
			Filamentous algae	6	7.1	6.1
			Myriophyllum sibiricum	1	1.2	1.0
			Polygonum amphibium	13	15.3	13.1
			Rannunculus longirostris	3	3.5	3.0
			Schoenoplectnus acutus	29	34.1	29.3
			Stuckenia pectinata	58	68.2	58.6
Martinez Lake	100	70	*Chara spp.*	2	2.9	2.0
			Filamentous algae	2	2.9	2.0
			Najas marina	68	97.1	68.0
			Phragmites communis	3	4.3	3.0
			Schoenoplectnus acutus	4	5.7	4.0
			Stuckenia pectinata	4	5.7	4.0
			Typha spp.	5	7.1	5.0
Mittry Lake	100	45	*Ceratophyllum demersum*	7	15.6	7.0
			Chara spp.	2	4.4	2.0
			Filamentous algae	1	2.2	1.0
			Najas marina	41	91.1	41.0
			Phragmites communis	4	8.9	4.0
			Potamogeton pusillus	2	4.4	2.0
			Schoenoplectnus acutus	4	8.9	4.0
			Stuckenia pectinata	7	15.6	7.0
			Typha spp.	5	11.1	5.0
Nelson Reservoir	100	100	*Ceratophyllum demersum*	32	32.0	32.0
			Chara spp.	14	14.0	14.0
			Elodea bifoliata	5	5.0	5.0
			Filamentous algae	99	99.0	99.0
			Myriophyllum sibiricum	41	41.0	41.0
			Polygonum amphibium	2	2.0	2.0
			Rannunculus longirostris	4	4.0	4.0
			Stuckenia pectinata	37	37.0	37.0
			Typha spp.	1	1.0	1.0

Lake	No. points surveyed	No. points with plants	Taxa	No. points with taxa	% Composition	% Frequency
			Unknown Nelson macrophyte1	4	4.0	4.0
Parker Canyon Lake	100	94	*Cyperus odoratus*	2	2.1	
			Filamentous algae	7	7.4	
			Myriophyllum spicatum	93	98.9	
			Nitella spp.	2	2.1	
			Schoenoplectnus acutus	1	1.1	
Pasture Canyon Lake	100	100	*Ceratophyllum demersum*	48	48.0	48.0
			Chara spp.	45	45.0	45.0
			Eleocharis palustris	1	1.0	1.0
			Filamentous algae	4	4.0	4.0
			Myriophyllum sibiricum	58	58.0	58.0
			Schoenoplectnus acutus	14	14.0	14.0
			Stuckenia pectinata	23	23.0	23.0
Patagonia Lake	100	22	Algae 1 Patagonia	2	9.1	
			Algae 2 Patagonia	2	9.1	
			Algae 3 Patagonia	5	22.7	
			Ceratophyllum demersum	1	4.5	
			Chara spp.	1	4.5	
			Najas marina	1	4.5	
			Typha spp.	16	72.7	
Pena Blanca Lake	100	99	*Ceratophyllum demersum*	98	99.0	
			Filamentous algae	36	36.4	
			Spirodela polyrhiza	4	4.0	
			Typha spp.	14	14.1	
Quigley Pond	100	31	*Chara spp.*	3	9.7	3.0
			Filamentous algae	26	83.9	26.0
			Typha spp.	10	32.3	10.0
Rainbow Lake	100	99	*Ceratophyllum demersum*	77	77.8	77.0
			Chara spp.	1	1.0	1.0
			Eleocharis parishii	1	1.0	1.0
			Elodea bifoliata	44	44.4	44.0
			Filamentous algae	41	41.4	41.0
			Myriophyllum spicatum	59	59.6	59.0
			Polygonum amphibium	6	6.1	6.0
			Pontederia spp.	7	7.1	7.0
			Potamogeton pusillus	12	12.1	12.0
			Schoenoplectnus acutus	1	1.0	1.0
Riggs Flat Lake	100	63	*Chara spp.*	39	61.9	39.0
			Eleocharis spp.	1	1.6	1.0
			Filamentous algae	42	66.7	42.0
			Myriophyllum spicatum	54	85.7	54.0
			Potamogeton pusillus	39	61.9	39.0

Lake	No. points surveyed	No. points with plants	Taxa	No. points with taxa	% Composition	% Frequency
			Rannunculus longirostris	3	4.8	3.0
Roper Lake	100	51	*Chara spp.*	31	60.8	31.0
			Filamentous algae	8	15.7	8.0
			Najas marina	39	76.5	39.0
			Potamogeton filiformis	1	2.0	1.0
			Stuckenia pectinata	7	13.7	7.0
			Typha spp.	3	5.9	3.0
Rose Canyon Lake	100	4	*Schoenoplectnus acutus*	1	25.0	1.0
			Typha spp.	3	75.0	3.0
Stoneman Lake	100	100	*Ceratophyllum demersum*	72	72.0	72.0
			Chara spp.	87	87.0	87.0
			Elodea bifoliata	27	27.0	27.0
			Filamentous algae	9	9.0	9.0
			Myriophyllum sibiricum	2	2.0	2.0
			Polygonum amphibium	19	19.0	19.0
			Schoenoplectnus acutus	18	18.0	18.0
			Sparganium spp.	1	1.0	1.0
			Stuckenia pectinata	96	96.0	96.0
Topock Marsh	180	137	*Chara spp.*	36	26.3	20.0
			Najas marina	112	81.8	62.2
			Schoenoplectnus acutus	12	8.8	6.7
			Stuckenia pectinata	60	43.8	33.3
			Typha spp.	7	5.1	3.9
Tsalie Lake	100	70	*Ceratophyllum demersum*	62	88.6	62.0
			Chara spp.	3	4.3	3.0
			Filamentous algae	34	48.6	34.0
			Myriophyllum sibiricum	35	50.0	35.0
			Potamogeton pusillus	2	2.9	2.0
Willow Creek Lake	100	84	*Azolla filiculoides*	6	7.1	6.0
			Ceratophyllum demersum	1	1.2	1.0
			Chara spp.	4	4.8	4.0
			Crypsis schoenoides	2	2.4	2.0
			Eleocharis palustris	4	4.8	4.0
			Eleocharis parishii	1	1.2	1.0
			Elodea bifoliata	39	46.4	39.0
			Filamentous algae	68	81.0	68.0
			Lemna minima	1	1.2	1.0
			Myriophyllum sibiricum	4	4.8	4.0
			Najas guadalupensis	3	3.6	3.0
			Najas marina	1	1.2	1.0
			Polygonum amphibium	7	8.3	7.0
			Potamogeton foliosus	1	1.2	1.0

Lake	No. points surveyed	No. points with plants	Taxa	No. points with taxa	% Composition	% Frequency
			Potamogeton pusillus	13	15.5	13.0
			Stuckenia pectinata	58	69.0	58.0
			Veronica anagallis-aquatica	1	1.2	1.0
Woodland Lake	100	100	*Ceratophyllum demersum*	35	35.0	35.0
			Elodea bifoliata	80	80.0	80.0
			Filamentous algae	46	46.0	46.0
			Myriophyllum sibiricum	81	81.0	81.0
			Polygonum amphibium	2	2.0	2.0
			Schoenoplectnus acutus	1	1.0	1.0
			Stuckenia pectinata	42	42.0	42.0
			Typha spp.	1	1.0	1.0

Table A2. Results of forward-stepwise logistic regressions showing coefficients with standard errors, Wald statistics, probabilities, and –2 times log-likelihood (-2 LL) of the included variables in the final models. Elevation (m), average depth (m), and average area (ha) were input into each model. Models for coontail, creeping spikerush, Eurasian watermilfoil, small pondweed, and hard-stem bulrush were not significant and are not shown.

Taxa	Variable	B	SE	Wald	P	-2 LL
Two-leaf elodea	Constant	-5.265	2.164	5.919	0.015	
	Elevation (m)	0.002	0.001	5.079	0.024	34.859
Northern watermilfoil	Constant	-2.273	1.204	5.111	0.024	
	Elevation (m)	0.001	0.001	4.272	0.039	43.251
Spiny naiad	Constant	2.007	1.084	3.431	0.064	
	Elevation (m)	-0.003	0.001	9.278	0.002	22.253
Water knotweed	Constant	-1.849	1.375	1.809	0.179	
	Elevation (m)	0.001	0.001	4.403	0.036	32.603
	Depth (m)	-0.224	0.104	4.670	0.031	
Water buttercup	Constant	-12.679	5.630	5.072	0.024	
	Elevation (m)	0.005	0.003	4.235	0.040	18.551
Sago pondweed	Constant	0.958	0.548	3.060	0.080	
	Depth (m)	-0.188	0.082	5.261	0.022	39.794
Cattail	Constant	2.627	1.150	6.672	0.022	
	Elevation (m)	-0.002	0.001	5.218	0.010	41.592