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Evaluation of Waterhyacinth Survival and Growth in the Sacramento Delta, California, Following Cutting

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ABSTRACT

Waterhyacinth (*Eichhornia crassipes* (Mart.) Solms), is a serious problem in the Sacramento Delta, currently managed with herbicides and to a lesser extent biological control insects. The search for alternative methods continues. The purpose of this study was to test the hypothesis that waterhyacinth would not survive treatments made by three types of cutting machines mounted on boats and thus result in open water areas. Waterhyacinth mats were treated by machines 1 and 2 during September, 2003 at Lambert Slough, south of Sacramento, California and at the Dow Wetlands, near Antioch, California. In June 2004, machine 3 cut plants in the Dow Wetlands. Machine 1 sheared off the leaves resulting in many plant fragments and plants that consisted of floating stem bases with intact root systems. The cutting motions of machines 2 and 3 differed and these machines produced numerous plant fragments along with ramets that had been split along a vertical axis into nearly intact ramets with broken leaves. Plants collected immediately after the treatments and grown either in situ or in tubs in Davis, California began to produce new leaves within one week of treatment. Leaf production rates were higher for cut than for un-cut plants. Similarly, plant dry weight increased over the course of the experiments. All of the plants survived in the tub experiments and 65% of them survived in field enclosures for at least six weeks. At Lambert Slough, >50% of the surface was covered by floating plant debris (2446 g dry weight m^{-2} and 1589 g dry weight m^{-2}) after four and six weeks even though the expectation was that the material would sink and decompose within three weeks. Cutting waterhyacinth with the three machines evaluated in this study did not immediately (i.e., within six months) produce weed free areas of open water in habitats typical of those found in the Sacramento/San Joaquin Delta.

Key words: Eichorrinia crassipes, mechanical control, aquatic plant management.

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INTRODUCTION

The floating aquatic plant, waterhyacinth, is one of the world's worst weeds (Holm et al. 1977). Highly aerenchymous leaves are arranged in rosettes and contribute to plant buoyancy. Fibrous roots form on the stem at the base of the leaves and hang down into the water column from which they absorb nutrients (Center and Spencer 1981). Its attractive purple flowers produce viable seeds, but waterhyacinth propagates primarily vegetatively by forming ramets at the ends of stolons.

Waterhyacinth has been in California for at least one hundred years (Bock 1968). Since the 1980's, it has become a serious problem in the Sacramento/San Joaquin Delta, California (hereafter simply the Delta; Anderson 1990). It is prolific in this ecosystem and its biomass interferes with pumping stations for agricultural and domestic water supplies, and recreational activities. Excessive waterhyacinth biomass also affects water quality and prevents access to wetlands for desirable wildlife species. There is little published information on the ecology of waterhyacinth in this system. Using changes in plant fresh weight, Bock (1969) determined that growth and reproductive rates measured over short periods were similar to those reported for waterhyacinth in tropical regions. Watson and Cook (1982) used waterhyacinth from the Delta in experiments examining the role of gibberrellic acid in plant development. Watson et al. (1982) also used waterhyacinth from the Delta in an isozyme analysis for this species. Spencer and Ksander (2004) reported waterhyacinth tissue nitrogen levels and concluded that Delta populations of biological control insects (*Neochetina* spp.) were likely not limited by this aspect of plant quality.

In the Delta, waterhyacinth is managed with applications of the aquatic herbicides, 2,4-D, diquat, or glyphosate. Two species of weevils, *Neochetina bruchi* and *N. eichhorniae* (Coleoptera: Curculionidae) were introduced into the Delta in the mid-1980s (Stewart et al. 1988) as biological control agents. To date, the weevils have not had long-term impact on waterhyacinth growth (Anderson 1990). The search for alternative methods of managing waterhyacinth continues.

Mechanical cutting or harvesting aquatic weeds is a well-known management technique, however, it has not been used extensively for waterhyacinth control in California. In September, 2003 and June 2004 three different types of boats with cutting implements mounted on them were used to "treat" portions of the Sacramento Delta to evaluate their potential as a method for managing waterhyacinth. The cutting machines evaluated in this study along with estimates of their associated operating costs have been described by Greenfield (2004). In conjunction with this demonstration project, executed by the San Francisco Estuary Institute, we established experiments to determine survivorship and re-growth potential of waterhyacinth plants which had been subjected to cutting (treatment).

MATERIALS AND METHODS

In order to determine the response of waterhyacinth plants to cutting, we conducted five experiments in which fragments collected from field sites were grown in tanks at Davis, California. These experiments were designated "outdoor experiments."

In addition, we conducted two experiments in which fragments were grown in enclosures at the site of the treatment. Six of the seven experiments were conducted in fall, 2003 and one experiment was conducted in spring, 2004. The details of these experiments are given below.

Study Sites

Part of this work was conducted at a site south of Sacramento, California in Lambert Slough (38° 19.254" N, 121° 28.686" W, Figure 1). Waterhyacinth plants were abundant at this site, covering most of the slough from bank to bank. On September 7 and 8, 2003 a section of this slough was cut with a mechanical flail mounted on the front of a large airboat (machine 1). On September 15, 2003 a second harvester (machine 2) was used in an adjacent section of Lambert Slough west of the gravel road that bisected the slough. On September 26, 2003 machine 2 was also used to cut waterhyacinth at the Dow Wetlands near Antioch, California (38° 01.242" N, 121° 50.038" W, Figure 1). In early June, 2004 machine 3 was also used to cut waterhyacinth at the Dow Wetlands. The following descriptions of the cutting machines are based on information in Greenfield (2004). Machines 1 and 2 were built and operated by an independent contractor (Master's Dredging, Lawrence, KS). Machine 2 also known as the "AquaPlant Terminator" is 8.53 m long, 2.59 m wide, weighs 5.454 metric tons, and requires 0.6 to 1 m of water depth. It is equipped with sets of shredding blades at the front and rear of the boat, operated by separate engines. Machine 1 also known as the "Amphibious Terminator" is a modified airboat, having a set of flail chopper blades, and a standard airboat fan. Machine 3 known as the "Cookie Cutter," was leased and operated by a local contractor (Clean Lakes, Inc., Martinez, CA). The "Cookie Cutter" is a barge with two 1.83 m diameter counter rotating blades that propel the vessel and cut through all encountered plant material and sediments. It is commonly used for cutting channels in very dense wetland vegetation. Similarly designed vessels have been used for controlling water hyacinth in Lake Victoria, Africa.

Figure 1. Map of California showing the approximate locations of the Lambert Slough site (S) and the Dow Wetlands site (A).

Fragment Properties

In order to characterize plant fragments produced by cutting, we collected ten dip net samples of plant debris immediately after machine 1 had finished an initial cutting pass. We also collected samples from an area where machine 1 made 2 cutting passes. This material was returned to the Exotic & Invasive Weeds Research Unit in Davis, California for further processing. Plants cut once were placed in thirteen large tubs (152 L) and those from plants cut twice in six large tubs. Stem bases in each tub were separated from other types of fragments. The number of stem bases in each tub was counted and their combined fresh weights determined. The combined fresh weights of 25 randomly selected fragments were determined for each of five sub-samples of plants cut either once or twice. Fragment dry weights were determined by multiplying the fresh weight by the dry weight to fresh weight ratio (0.045 ± 0.004, mean ± standard error, N = 20) and dividing the result by the number of plants or fragments in the sample. The dry weight to fresh weight ratio was determined using data from other plants collected as part of this study.

Four of the sub-samples (25 pieces each) of waterhyacinth fragments from either cutting treatment were photographed using a Nikon Coolpix 5700 digital camera. Calibrated digital images were examined using SPSS Sigma Scan Pro (SPSS Inc., Chicago, IL) to determine fragment length. Following visual examination, 100 fragments from each cutting treatment were assigned to one of four categories: leaf (fragments with both petiole and leaf blade present), blade (fragments that were only leaf blade) petiole (fragments that were from petioles) and stem base (fragments that were part of the stem base and had pieces of root attached). Mean fragment lengths for each fragment type and the proportion of fragments in each category were determined.

The "cookie cutter" (machine 3) used in the 2004 Dow Wetlands treatment also produced several types of fragments. A large sample (approximately 150 L) of these fragments was collected following cutting on June 2, 2004. This material was returned to the Exotic & Invasive Weeds Research Unit in Davis, California and placed in large tubs of water for further processing. Ten sub-samples consisting of ten randomly selected fragments each were dried and weighed. Fragment dry weight was determined by dividing the sub-sample weight by ten. The mean of these ten fragment dry weights was calculated. Nine additional sub-samples (20 pieces each) of the waterhyacinth fragments were photographed as above. Lengths of 180 individual fragments were determined as above. We classified 180 of these fragments into the following seven categories: ramets (plants with intact leaves, stem base, and roots), leaf (both petiole and blade present), petiole, blade, roots, stem base, or stolon.

Outdoor Experiment 1

On the day the plants were cut by machine 1 at Lambert Slough, we collected several un-cut and cut plants which were returned to the laboratory facility in Davis, California. The plants were placed in individual152 L cylindrical plastic containers (0.79 m depth × 0.57 m diameter) filled with 0.56 m of water. At the start of the experiment, 30.5 g of KNO_3 was added to each container to supplement nitrogen availability. (Given the expected release of nitrogen by decomposing waterhyacinth in the field this does not seem unreasonable.) Ten un-cut plants served as controls, ten plants which had been through the flail once, and ten plants which had been through the flail twice were used for a total of 30 containers. This was designated outdoor experiment 1. Additional plants were dried (96 h, 80 C) to determine starting dry weight. We photographed the plants in each container weekly. The photographs were examined for leaf number and relative growth rates (RGR) based on the number of leaves present were calculated by linear regression of log (leaf number) versus time (days) (Hunt 1982). We also calculated survivorship for these plants by recording the date that plants died. In this and outdoor experiments 2, 3, 4, and 5 all plants grew outside on a concrete pad and thus were exposed to ambient conditions between June 1 and August 1. During this period the following conditions prevailed: mean maximum daily air temperature was 31.5 C, mean minimum daily air temperature was 12.7 C, mean daily incident solar radiation was 339 W m^{-2}, mean maximum relative humidity was 82%, mean minimum daily relative humidity was 295. These data are based on data obtained from the University of California Integrated Pest Management System, Davis Station A (http://ipm.ucdavis.edu), which may be consulted for more details.

Outdoor Experiment 2

On September 15, 2003 machine 2 was used in an adjacent section of Lambert Slough west of the gravel road that bisected the slough. Four days after the cutting machine went through this section, we collected both cut and un-cut plants. The plants were returned to the laboratory, the total number of leaves counted and the number of leaves that were removed by the harvester recorded based on the presence of cut petioles still attached to the stem base. Five cut and un-cut plants were placed in individual 76-L rectangular plastic containers (0.44 m length × 0.43 m width × 0.45 m deep) filled with water (0.34 m deep) and added nutrients as above. Their survival and growth were monitored weekly as described above.

Outdoor Experiment 3

To determine if fragments produced by machine 1, which could have floated away after cutting and eventually became stranded on a mudflat or similar area could survive, we conducted an additional study. For this experiment, ten waterhyacinth fragments from plants that had been cut either once or twice were selected. We selected fragments that consisted of a section of the stem base with attached roots. Individual fragments were placed in small plastic trays (0.2 m length × 0.2 m width × 0.06 m deep) filled with topsoil. The bottom of the trays were perforated and the trays were placed in a large shallow fiberglass tub (1.83 m length × 1.1 m width × 0.13 m deep) that was filled with just enough water (0.06 m deep) to maintain the topsoil at saturated conditions. Water lost to evaporation was replaced weekly or as otherwise needed. Fragments were photographed weekly to record the presence of newly produced leaves.

Outdoor Experiment 4

On September 26, 2003, we collected both cut and un-cut plants from the Dow Wetlands (machine 2). The plants were returned to the laboratory, the total number of leaves counted and the number of leaves that were removed by the harvester recorded based on the presence of cut petioles still attached to the stem base. Ten cut and un-cut plants were placed in individual 76-L rectangular plastic containers (0.44 m length × 0.43 m width × 0.45 m deep) filled with water (0.34 m deep) their survival and growth were monitored weekly as above. After six weeks, plants were harvested, dried, weighed as above.

Outdoor Experiment 5

On June 2, 2004, cut and un-cut plants were collected from the Dow Wetlands following cutting by machine 3. The plants were returned to the laboratory, the total number of leaves counted, plant height measured, ten control and ten cut plants were dried (96 h, 80 C) and weighed. Starting dry weights of experimental plants were determined by multiplying the starting fresh weights by a dry weight to fresh weight ratio determined for these plants. The plants were placed in individual152 L cylindrical plastic containers (0.79 m depth × 0.57 m diameter) filled with 0.56 m of water. Ten un-cut plants served as controls, ten plants which had been through the harvester were the treated plants. We photographed the plants in each container weekly. The photographs were examined for leaf number and number of new ramets. After six weeks, plants were harvested, dried, weighed as above. Relative growth rates (RGR) based on the number of leaves, the number of ramets, and changes in dry weight were calculated as above. Differences in RGR for treated and control plants were assessed by comparing 95% confidence intervals.

Field Experiment 1

Immediately after the cutting treatments, we established three enclosures along one bank of Lambert Slough. The enclosures were constructed by attaching plastic construction fencing (4 cm × 5 cm mesh size) with plastic cable ties, to 2.5 cm diameter, 2.4 m long PVC pipes which were hammered into the sediment. The enclosure included a band of un-cut plants, which served as control plants, that extended from the bank outward about 50 cm. In addition ten plants which had been through the harvester were marked by placing a cable tie around the stolon or any remaining petiole. Once a week for the following six weeks, the plants were counted to determine percent survival. Five, fourteen, and forty-two days after treatment the number of leaves present on the control and cut waterhyacinths was recorded. The relative growth rate (RGR) based on leaf number was calculated as above. The effect of cutting on RGR was tested by comparing the 95% confidence intervals for the regression coefficient (i.e., RGR). All statistical analyses were calculated with SAS (SAS Institute 1999).

We estimated the proportion of the slough covered with cut waterhyacinth and fragments and the proportion of open water present. We did this by measuring the length of slough that had plants present and that which had open water except for a fringe of un-cut plants.

Four and six weeks after cutting, we counted the number of waterhyacinth ramets present in ten, 0.2 × 0.3 m, quadrats in both treated and untreated areas adjacent to but outside of the enclosures. We collected ten un-cut plants and ten cut plants to determine, plant height, number of leaves, leaf dry weigh, root dry weight, and stem base dry weight per plant. In addition we collected the floating debris consisting of cut waterhyacinth pieces that were present in four additional quadrats also outside of the enclosures. The dry weight of this material was determined (96 h at 80 C). Waterhyacinth biomass was estimated by multiplying the mean number of ramets per square meter (m^{-2}) by mean ramet weight. Standing crop m^{-2} was estimated by adding the dry weight of waterhyacinth fragments m^{-2} to the biomass m^{-2} estimates. The effect of cutting on these variables was tested by analysis of variance (ANOVA) calculated with the GLM procedure in SAS (SAS Institute 1999).

Field Experiment 2

On September 26, 2003 machine 2 was deployed in the Dow Wetlands. Immediately following its cutting passes, we established a large enclosure (7 m × 3 m) adjacent to an existing dock. We tagged twenty cut plants and placed them in the enclosure. The plants were photographed weekly to determine re-growth and survival. Un-cut plants in an adjacent enclosure served as control plants. After seven weeks, plants were harvested, dried as above, and weighed.

RESULTS

Fragment Properties

Cutting waterhyacinth plants with the airboat-mounted flail used in the Lambert Slough produced various sized plant fragments (Figure 2). Fragments containing both

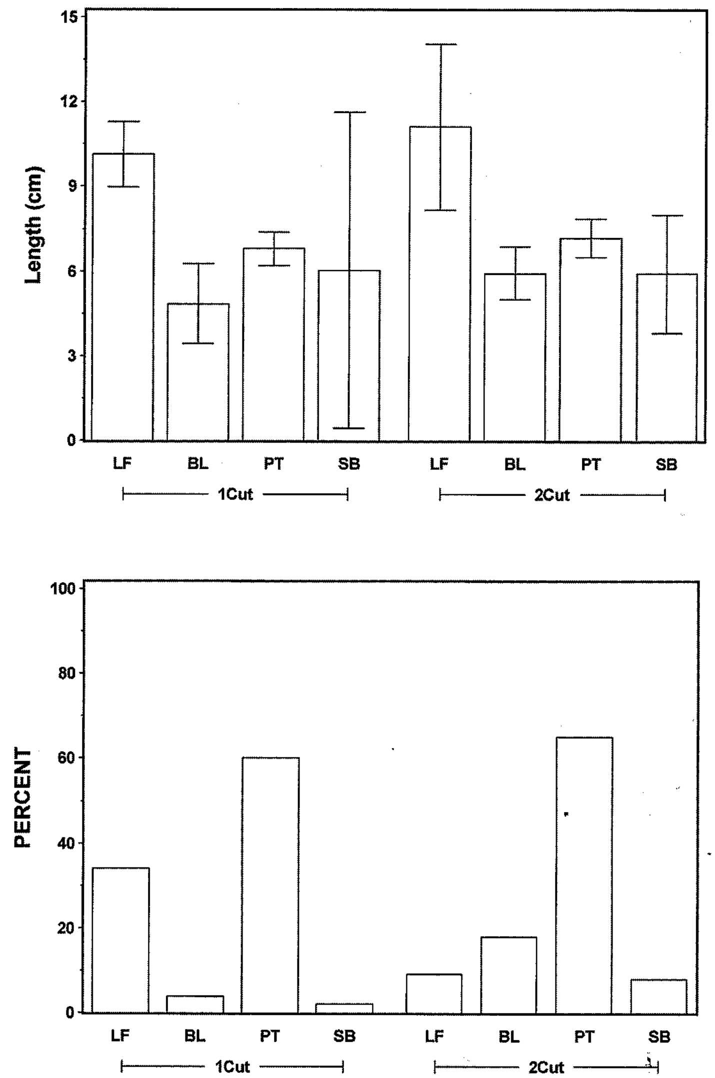

Figure 2. Mean lengths for waterhyacinth fragments produced by 1 or 2 cuttings (upper graph). Values are mean ± 95% confidence intervals. LF = Entire Leaf (i.e., containing a portion of the leaf blade and petiole), BL = Leaf blade, PT = Petiole, SB = Stem base. The lower graph shows relative proportions (as %) of fragment types produced. A total of 100 fragments from each treatment were measured and classified.

blade and petiole sections were longest and those which were only leaf blade pieces were shortest. Cutting the plants either once or twice did not result in detectable differences in lengths for different types of fragments (Figure 2). The effect of cutting the plants twice was to produce fewer pieces that resembled entire leaves and more pieces that were classified as either parts of leaf blades or petioles (Figure 2). Mean fragment dry weight (0.117 ± 0.009 g, ± standard error (S.E.), N = 5) for plants cut once did not differ from that of plants cut twice (0.128 ± 0.009 g, ± S.E., N = 5) based on the results of Student's t-test (t = -0.91, df = 8, P = 0.39). Similarly, the mean dry weights of stem bases from plants cut once (4.72 ± 0.42 g, ± S.E., N = 13) did not differ from those cut twice (3.50 ± 0.96 g, S.E., N = 6) based on the results of Student's t-test (t = 1.37, df = 17, P = 0.19). The "cookie cutter" machine used in the 2004 Dow Wetlands treatment produced several types of fragments. Fragment lengths varied from 0.6 cm to 33 cm with a mean value of 7.1 cm. The coefficient of variation for fragment length was 70%. Fragments classified as stem bases and leaves were the longest fragments and those consisting only of roots the shortest (Figure 3). Most abundant type of fragments were ramets, leaves, or pieces of stolon (Figure 3). Mean fragment dry weight was 0.582 ± 0.05 g, N = 10.

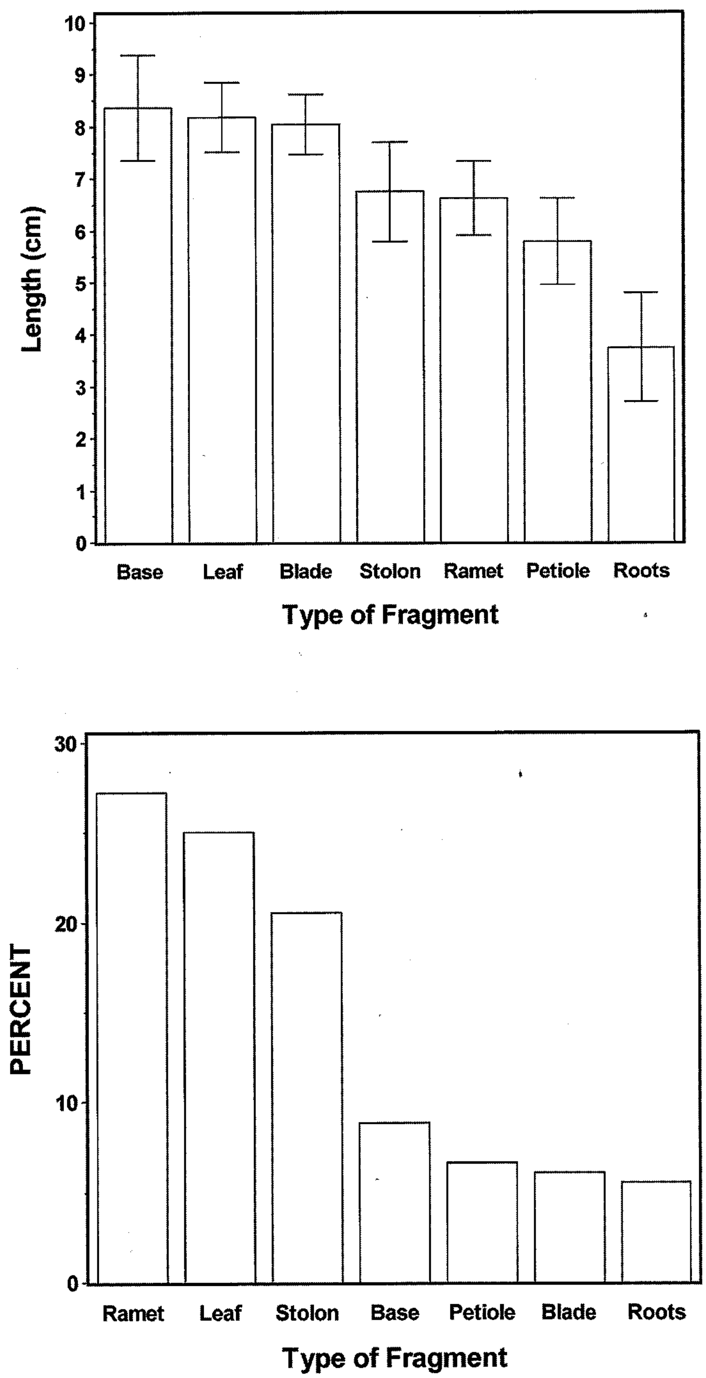

Figure 3. Characteristics of fragments produced by machine 3 at the Dow Wetlands in 2004. Mean length (± 95% confidence intervals) (upper graph) and frequency (lower graph) for different categories of fragments.

Outdoor Experiment 1

Waterhyacinth plants placed in outdoor tubs in experiment 1 grew well. Mean number of leaves per plant reached 60 within three weeks for control plants. The mean remained near this value for an additional two weeks and then began to decline, likely due to depletion of nutrients in the water and decreasing temperatures. Plants which had been cut either once or twice began to produce new leaves within a week. Compared to plants cut once, slightly fewer new leaves were produced by plants which had been cut twice. All of the plants in each treatment survived six weeks in this study. The rate at which new leaves were produced was significantly greater for plants which had been cut once than for control plants or plants that had been cut twice (Table 1). Overlapping 95% confidence intervals suggest that there was no difference in the leaf production rate for control plants or those that had been cut once or twice.

Outdoor Experiment 2

All of the cut and control plants survived for the six weeks, indicating that cutting by machine 2 did not necessarily result in plant mortality. As with outdoor experiment 1, waterhyacinth produced new leaves within a week of the start of the experiment. RGR based on the number of leaves was significantly greater for cut plants than for control plants (Table 1). After six weeks growth, there were no significant differences in plant height (27.7 ± 1.2 cm versus 24.4 ± 4.6 cm, mean ± standard error, P = 0.5, t-test), number of leaves per plant (38.0 ± 8.2 leaves versus 23.0 ± 3.7 leaves, mean ± standard error, P = 0.15, t-test), or dry weight (26.9 ± 9.6 g versus 15.0 ± 3.1 g, mean ± standard error, P = 0.29, t-test). Comparison of the amounts of biomass allocated to different plant parts indicates that cut plants were able to maintain leaves by reducing the relative amount of biomass allocated to roots (Figure 4).

Outdoor Experiment 3

In experiment 3 in which fragments from Lambert Slough were grown on saturated soil, 70% of the fragments from plants cut once and 50% of the fragments from plants cut twice survived. The surviving fragments had begun to produce new leaves by three weeks after being planted. The rate of leaf production (RGR) was less than those observed in outdoor experiments 1 and 2, but there was no significant difference between the two cutting treatments (Table 1).

Outdoor Experiment 4

In outdoor experiment 4 using plants from the Dow Wetlands, the number of leaves per plant increased from around 14 to nearly 60 for control plants and from 2 to 23 for waterhyacinth which had been cut. Comparison of the 95% confidence intervals for the leaf production rates indicate that this rate was significantly higher for plants which had been cut than for control plants (Table 1). Control plants were taller than cut plants, but plant height did not change measurably during this study (data not shown).

TABLE 1. RELATIVE GROWTH RATES (RGR) BASED ON LEAF NUMBER FOR WATERHYACINTH IN SEVEN EXPERIMENTS. VALUES IN PARENTHESIS ARE THE 95% CONFIDENCE LIMITS.

Experiment	RGR (leaves leaf^{-1} day^{-1})		
	Control	Cut once	Cut twice
Outdoor 1	0.064 (0.031-0.098)	0.122 (0.078-0.167)	0.072 (0.027-0.118)
Outdoor 2	0.032 (0.022-0.042)	0.058 (0.048-0.068)	—
Outdoor 3	—	0.027 (0.005-0.050)	0.020 (0.004-0.036)
Outdoor 4	0.046 (0.040-0.052)	0.074 (0.060-0.087)	—
Outdoor 5	0.058 (0.050-0.067)	0.042 (0.034-0.051)	
Field 1	0.007 (0.002-0.012)	0.031 (0.026-0.036)	—
Field 2	-0.002 (-0.008-0.004)	0.040 (0.029-0.051)	—

Outdoor Experiment 5

In outdoor experiment 5 using plants collected from the Dow Wetlands in June, 2005, mean plant height was somewhat lower but not significantly so for cut plants compared to un-cut plants. However starting dry weights were significantly different. Over the course of the six-week experiment the dry weight of both cut and un-cut plants increased (Figure 5). Comparison of the 95% confidence intervals for RGR based on dry weight indicates that rates were similar for cut and un-cut plants (Figure 5). The number of leaves and ramets per plant also increased over time for both cut and un-cut plants. RGR based on the leaf data were lower for the cut plants, based on comparisons of the 95% confidence intervals the decrease was not significant (Table 1).

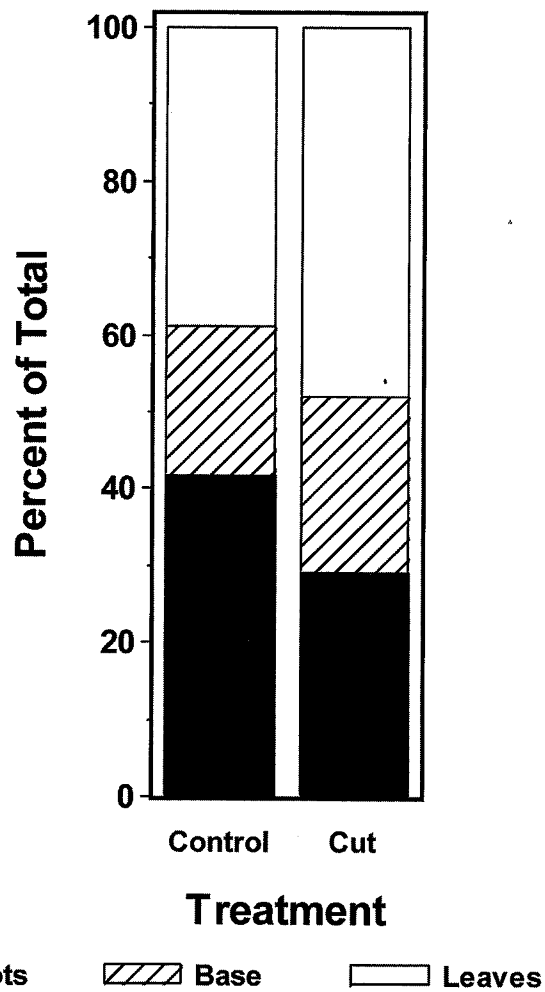

Figure 4. Allocation of biomass to plant parts for waterhyacinth grown six weeks in outdoor experiment 2. Leaves include both leaf blade and petiole and base refers to the stem base.

Field Experiment 1

All control plants survived six weeks in the enclosures in field experiment 1. Cut plants had reduced survival, but 65% of these plants were viable after six weeks (Figure 6). New leaves were present on the cut plants within 14 days after cutting (note, we only visited this site once a week). Leaf production (RGR) was significantly greater for cut plants than for control plants. In fact, the RGR for leaf production by cut plants was four times that of control plants (Table 1). Samples collected outside the enclosures show that the number of ramets m^{-2} either 28 or 42 days after cutting was not affected by cutting but the biomass and standing crop were (Table 2, Figure 7). At 28 days after cutting, biomass was reduced by 58% and standing crop by 25% relative to un-cut areas. Standing crop includes all plant material, either alive or dead and thus includes the dry weight of floating debris which resulted from cutting. At 42 days after cutting, biomass was reduced by 39% and standing crop by 11% relative to un-cut areas. Examination of individual plants collected 28 days after cutting, showed that cut plants were shorter, had fewer leaves, reduced leaf, root, stem base, and total dry weights on average (Table 2). The dry weight of stem bases were not significantly different for cut or control plants. These results indicate that new leaf growth was supported by reducing the amount allocated to root production.

The proportion of the area of Lambert Slough covered by floating waterhyacinth decreased by slightly more than 20%, by a week after cutting (Figure 8). However, >50% of the surface was covered by waterhyacinth at six weeks after cutting (Figure 8).

This was unexpected because it had been predicted that the floating debris produced by the cutting would sink and decompose within three weeks after cutting. In fact, the dry weight of floating debris was nearly 2446 g m^{-2} and 1589 g m^{-2} on October 6 and October 20, four and six weeks after cutting, respectively.

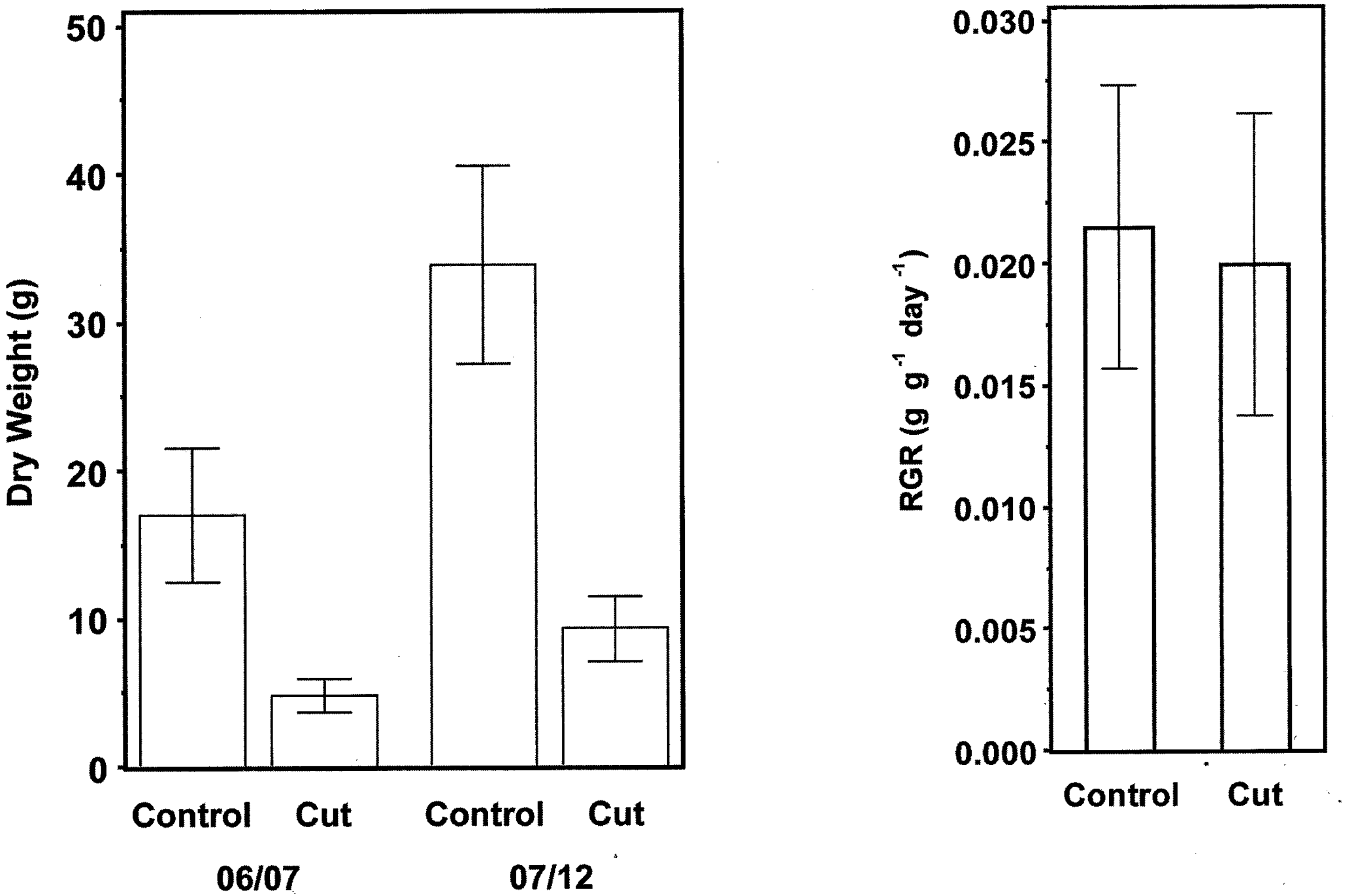

Figure 5. Waterhyacinth dry weights (left) for cut and control (un-cut) plants at the beginning and end of outdoor experiment 5. Bars represent the mean and 95% confidence interval. The right panel shows the RGR based on changes in dry weight over the course of the experiment. In this graph, the error bars represent the 95% confidence intervals for RGR.

Field Experiment 2

In the Dow Wetlands field study, all control plants and 70% of the cut plants survived six weeks in the field enclosures. Starting plant height was significantly less for cut plants compared to un-cut control plants. Starting dry weights were significantly different (Figure 9). Over the course of the seven-week experiment the dry weight of both cut and un-cut plants increased (Figure 9). Comparison of the 95% confidence intervals for RGR based on dry weight indicates that rates were similar for cut and un-cut plants (Figure 9. The number of leaves per plant increased for cut, but not for un-cut plants. RGR using leaf number was significantly lower for the un-cut plants, based on comparisons of the 95% confidence intervals (Table 1).

DISCUSSION

Waterhyacinth treated with the cutting machines in this study were typical in size of those found in the Delta (Spencer and Ksander 2005). Mean ramet dry weights at the time of cutting ranged 21 to 41 g dry weight, and the ramets were from 18 to 87 cm tall. Ramet density at the Lambert Slough site was approximately 98 m^{-2} at the time the treatments were made.

Waterhyacinth plants subjected to cutting at the end of the growing season produced new leaves within one week of being cut by machine 1. Machine 1 completely shaved off the tops of the plants leaving a stem base with attached roots in most cases, so this result indicates that the plants were able to respond to severe damage by initiating new leaf growth. In fact, plants which had been cut either once or twice by machine 1 produced new leaves more rapidly than did plants which had not been cut at all. It is also noteworthy that shearing off the leaves with the resulting exposure of the stem base tissues to the surrounding water did not lead to rapid invasion of the plant by microbes sufficient to cause plant death, as 65% of test plants survived at least six weeks under field conditions. This may be in part because waterhyacinth have specialized cells involved in the production of phenolic compounds which may inhibit growth of microbes (Martyn and Cody 1983).

Results from experiment 3, indicate that from 50% to 70% of waterhyacinth fragments that may become stranded in mudflats or similar areas can survive and produce new plants. This result was obtained with fragments that had

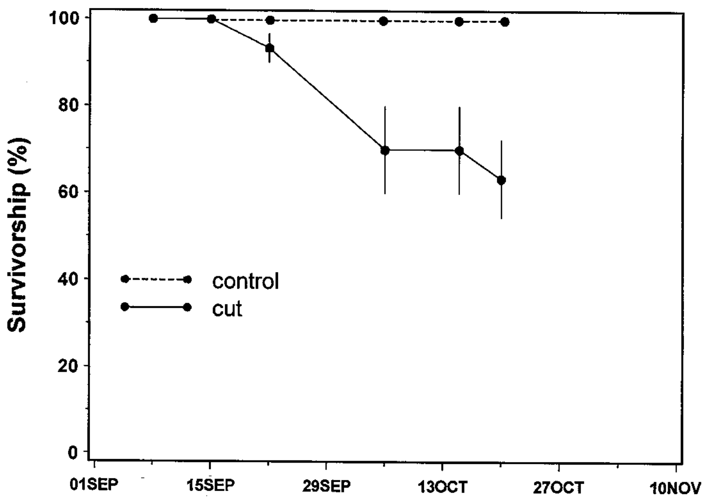

Figure 6. Survival of marked waterhyacinth plants that had been cut once and were placed in enclosures, field experiment 1. Values are the mean (± standard error) survivorship of ten plants in each of three enclosures, thus there were 30 total plants. All of the control plants in the enclosures survived for the six week duration of this study.

been cut by machine 1 either once or twice. The fragments in this experiment also had some portion of the stem base along with some roots still attached. Measurements from Lambert Slough indicate that from 3 to 10% of all fragments produced by machine 1 would be included in this category.

Machines 2 and 3 had less physical impact on the plants than machine 1. For example, fragments produced by machine 3 were larger than those produced by machine 1 and in many cases resembled more or less intact ramets. In the outdoor and field experiments, measures of plant growth for treated plants were of similar or greater magnitude than those for untreated plants. One exception was for plants cut with machine 3 in June of 2004 at the Dow wetlands. For these plants the rate of leaf production was 28% lower for cut than for untreated plants. But, the June 2004 treatment was actually the second time that the Dow wetlands area was cut, so it is not certain that the slightly reduced growth was only due to the effects of cutting by machine 3. It is also possible that cutting the plants at the end of a growing season and relatively early in the subsequent growing season may prevent the accumulation of sufficient stored reserves to allow the plants to recover more rapidly. The reduced recovery indicated by lower leaf production rates for waterhyacinth cut in June is also in agreement with the findings of Luu and Getsinger (1990). They presented data on total nonstructural carbohydrate (TNC) concentrations in waterhyacinth stem bases grown in outdoor cultures in Mississippi. Luu and Getsinger (1990) indicate that TNC values for June were about 5% of dry weight while those in September were between 30 and 35% of dry weight. Thus, plants subjected to cutting in September would have greater stored reserves with which to produce new leaves. It is noteworthy that even with lower stored reserves a detectable fraction (30% to 70%) of the cut plants did recover and produce new leaves.

In all of the experiments, plants that survived the cutting treatments were smaller than un-cut control plants. However, for plants at Lambert Slough, we observed that these smaller plants were nearer the water surface did not suffer as much frost damage as did the taller un-cut control plants at this site. This may in fact permit the surviving plants to start growing earlier in the following growing season.

The focus of this study was on the impact of the cutting machines on waterhyacinth and subsequent impacts of the plant material left in place. We did not assess direct impacts of these cutting machines on animals that may live near the waterhyacinth mats, such as insect, fish, frogs, turtles, or

TABLE 2. RESULTS OF ANALYSIS OF VARIANCE (ANOVA) FOR THREE MEASURES OF WATER HYACINTH ABUNDANCE IN LAMBERT SLOUGH ON TWO SAMPLING DATES.

	Source	DF	Type III SS	Mean square	F Value	Pr > F
Standing crop (g m-2)						
	Date	1	2366.98	2366.98	0.02	0.8810
	Cutting	1	886201.29	886201.29	8.51	0.0061
	Date*Cutting	1	172348.76	172348.76	1.65	0.2065
	Error	36	3749108.05	104141.89		
	Corrected Total	39	4810025.09			
Biomass (g m-2)						
	Date	1	893.03	893.03	0.01	0.9343
	Cutting	1	5825861.81	5825861.81	44.92	<.0001
	Date*Cutting	1	243724.13	243724.13	1.88	0.1789
	Error	36	4669010.73	129694.74		
	Corrected Total	39	10739489.70			
Ramets (number m-2)						
	Date	1	173.61	173.61	0.23	0.6366
	Cutting	1	173.61	173.61	0.23	0.6366
	Date*Cutting	1	1562.50	1562.50	2.04	0.1615
	Error	36	27527.78	764.66		
	Corrected Total	39	29437.50			

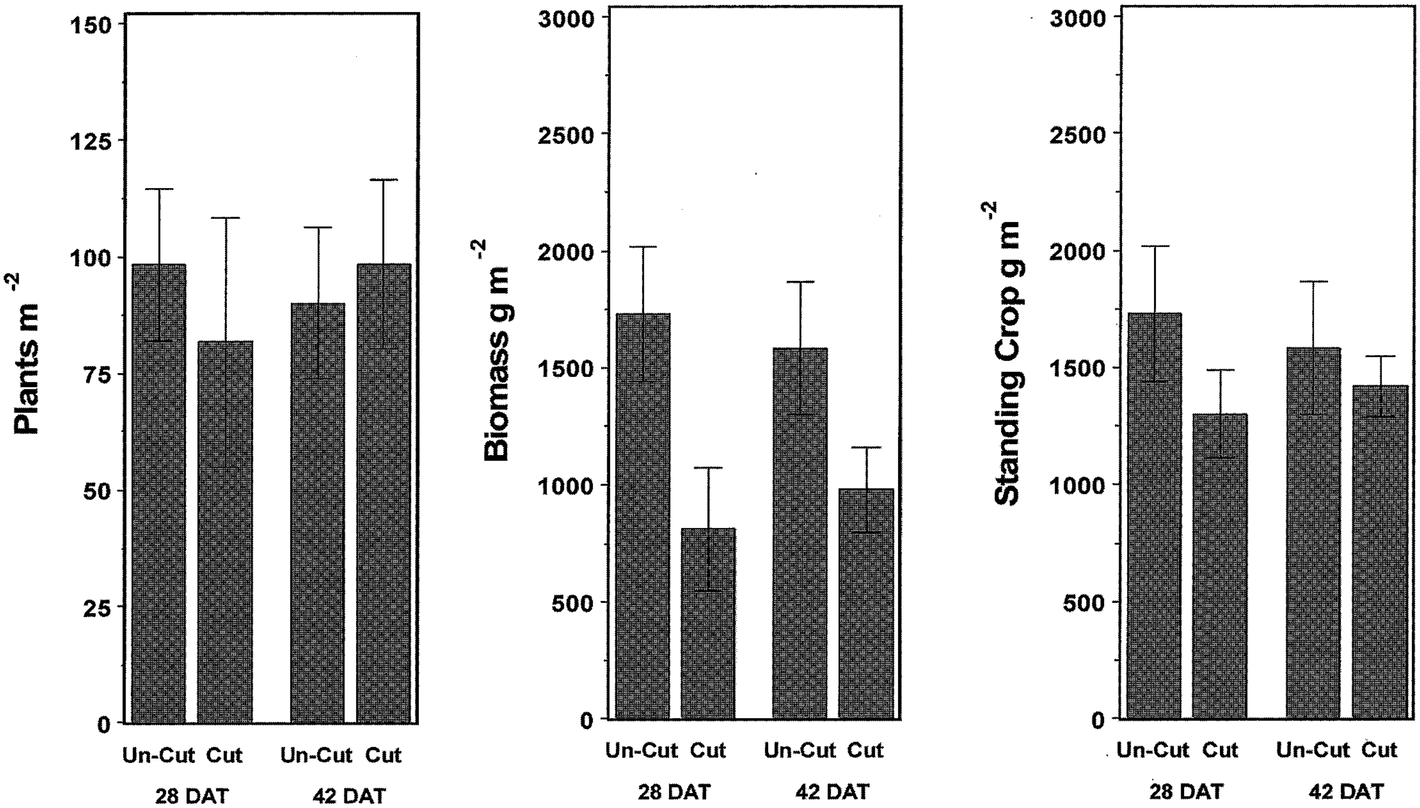

Figure 7. Waterhyacinth characteristics for plants collected from inside enclosures in field experiment 1, 28 and 42 days after treatment, October 6, and October 20, 2003, respectively.

birds, although previous studies with aquatic plant harvesters have reported such impacts (Haller et al. 1980, Mikol 1985, Engel 1990, Booms 1999).

All of the cutting treatments produced considerable floating debris consisting of various sizes and types of waterhyacinth fragments. The ultimate decomposition of this material releases nutrients into the water column (Ahmed et al. 1982). For example, one month after cutting, there was approximately 2445.8 ± 96.7 (S.E.) g dry weight m^{-2} of floating debris present at Lambert Slough. Spencer and Ksander (2004) reported that tissue N and C varied seasonally for Delta waterhyacinth, and that on average Delta waterhyacinth would contain 1.55% dry weight nitrogen (N) on a whole plant basis in August. Thus at Lambert Slough, the complete decomposition of waterhyacinth floating debris would contribute a minimum of 37.9 ± 1.5 (S.E.) g N m^{-2} to the water column. Similarly, this amounts to an addition of 909.4 ± 36 (S.E.) g C m^{-2} to the water column. Values for waterhyacinth tissue P were obtained from Klumpp et al. (2002) who reported values for plants with similar tissue N values as those used above (i.e., mean tissue N was 1.84% or 2.02%). The mean value for stem and root tissue P for these plants was 0.24% dry weight. Using this value, indicates that decomposition of waterhyacinth floating debris would contribute a minimum of 5.88 ± 0.23 (S.E.) g P m^{-2} to the water column. These nutrients would be available for uptake by recovering waterhyacinth plants as well as other plants and microbes.

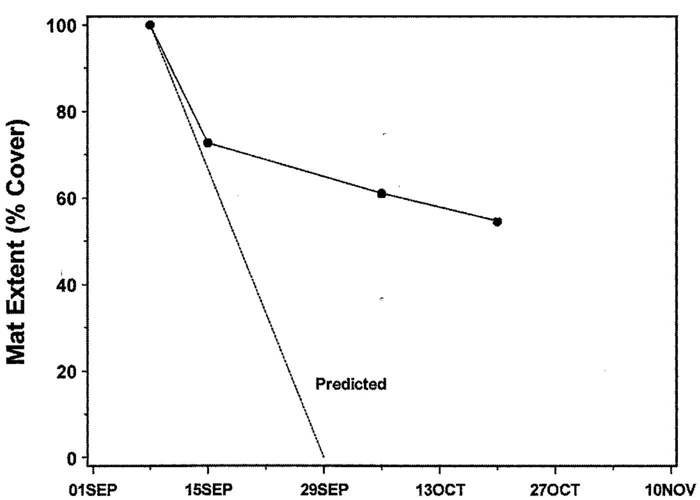

Figure 8. The proportion of Lambert Slough covered by waterhyacinth following cutting. The predicted line indicates estimated plant disappearance as three weeks following cutting.

It may take considerable time for the complete decomposition of this material. We observed that floating waterhyacinth debris covered >50% of the surface of the Lambert Slough site for at least six weeks following cutting. In fact, we visited and photographed this site periodically for more than a year after treatment. Significant quantities of floating debris remained even six months after treatment. The Lambert Slough

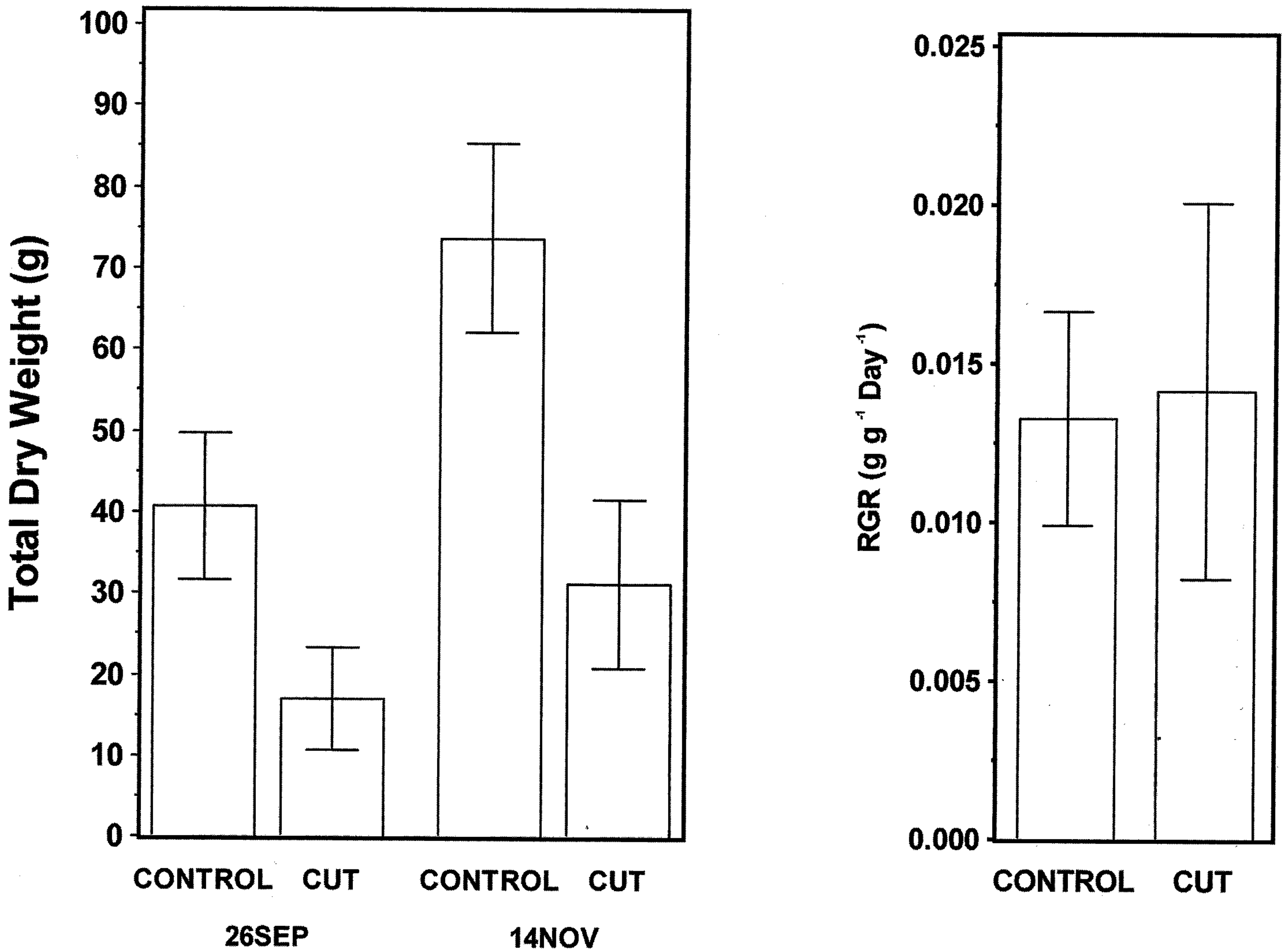

Figure 9. Waterhyacinth dry weights (left) for cut and control (un-cut) plants at the beginning (26 Sep) and end (14 Nov) of field experiment 2 conducted at the Dow Wetlands, Antioch, California. Bars represent the mean and 95% confidence interval. The right panel shows the RGR based on changes in dry weight over the course of the experiment. Error bars represent the 95% confidence intervals for RGR.

site was typical of more inland portions of the Delta, being more likely to be enclosed or surrounded on three sides by land and having reduced water exchange. Thus, debris produced in the cutting process may not be carried away rapidly by tidally influenced water movements. However, a similar response was noted at the Dow Wetlands for 2003, even though this area is much more influenced by tidal water movements. Debris may not persist for so long at more open sites.

There have been few studies involving cutting of floating aquatic plants such as waterhyacinth. Ntiba et al. (2001) discussed the possibility of using a cutting machine similar in appearance to machine 3 for managing waterhyacinth in Lake Victoria (Africa). But to date no published information on its impact on waterhyacinth is available. Methe et al. (1993) evaluated the efficacy of an air boat cutting system similar to machine 1. They used it to cut the emergent plant, waterchestnut (*Trapa natans* L.), in Watervliet Reservoir, New York. They reported that cut plants displayed a decrease in both leaf size and number, and that the number of buds, flowers, and pollinated flowers decreased for cut plants. However, they noted that cut plants survived and produced viable seeds. This led them to conclude that as a management practice cutting minimized but did not prohibit seed production by waterchestnut. Similarly, we observed that a significant portion of waterhyacinth plants survived cutting and started to re-grow within a week of being cut. We also conclude that cutting waterhyacinth plants with the three machines evaluated in this study did not immediately (< six months) either kill most of the plants or produce significant open water areas in habitats typical of those found in many parts of the Sacramento/San Joaquin Delta. Thus, cutting waterhyacinth with the machines evaluated in this study may be a management practice with limited effectiveness in areas of the Delta similar to those considered here.

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USDA Agricultural Research Service and by funds from the State of California provided to the San Francisco Estuary Institute. Mention of a manufacturer does not constitute a warranty or guarantee of the product by the U.S. Department of Agriculture nor an endorsement over other products not mentioned.

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Evaluating Impacts of Lake Maid™ Plant Control

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ABSTRACT

The Lake Maid™ is a mechanical control device for removing nuisance aquatic vegetation in small areas around docks (up to 200 m² at a time). Direct impacts of the Lake Maid™ on water quality and the potential for spread of viable plant fragments were evaluated in this study, conducted on the San Joaquin River Delta. Analyses of water nutrient concentrations (total and dissolved phosphorus, nitrate and nitrite, and organic carbon) and measurements of conventional water quality parameters as well as fragment density were conducted over a 10-day treatment period. A mesocosm experiment, plant biomass estimation, and a cost-effectiveness evaluation were also performed. The Lake Maid™ successfully removed all above ground plant biomass at two study sites and partially removed plant biomass at a third site without affecting nutrient concentrations or water quality in the treatment areas. The likelihood of spreading plant fragments is high, but in areas of extensive aquatic plant infestation, like the San Joaquin River Delta, this may not be a management concern. During the 10-day treatment period, the Lake Maid™ proved to be an effective, low-maintenance plant control method for removal of submersed vegetation in small areas where additional plant fragmentation is tolerable.

Key words: mechanical control, fragments, re-growth, San Joaquin River, *Egeria densa, Ceratophyllum demersum.*

INTRODUCTION

Introduced aquatic plants impair the use of water resources in many ways. Problems associated with exotic plants include degradation of water quality, interference with flood control measures, obstruction of boat traffic, and decreased

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