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Seasonal Growth of Waterhyacinth in the Sacramento/San Joaquin Delta, California

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ABSTRACT

Waterhyacinth (*Eichhornia crassipes* (Mart.) Solms), is a serious problem in the Sacramento/San Joaquin Delta, California. There is little published information on its phenology or seasonal growth in this system. Waterhyacinths were sampled at 2 to 3 week intervals from November, 1995 to July, 1997 and the following measurements were made on individual plants: dry weight, height, number of living leaves, number of dead leaves, and the width of the largest lamina. Lamina area per plant was estimated by multiplying the number of living leaves by the mean lamina area for each sampling date. We also noted the presence or absence of flowers. Height and dry weight increased from less than 10 cm in winter and early spring to more than 80 cm in late summer and from 10 g to 85 g, respectively. Number of dead leaves was greatest in the winter and declined through June. New leaves started to appear in March. Starting in March, lamina area per plant increased through October. Plants with flowers were present at the sample site from May 20 to August 12 but not abundant. A logistic regression equation relating relative lamina area per plant to accumulated degree-days was developed. Maximum growth was achieved in October, later than previously reported for waterhyacinth in southeast U.S. populations.

Key words: aquatic weeds, *Eichhornia crassipes*, phenology, integrated control, weed biology.

INTRODUCTION

The floating aquatic plant, waterhyacinth, is one of the world's worst weeds (Holm et al. 1977). Its free-floating plant body comprises of a shoot with a rosette of petiolate leaves, a terminal inflorescence and numerous roots hanging in the water (Gopal 1987). Its attractive purple flowers produce viable seeds, but waterhyacinth propagates primarily vegetatively by forming ramets at the ends of stolons. Books have been written about waterhyacinth (Gopal and Sharma 1981, Gopal 1987) and the Journal of Aquatic Plant Management has published more than 100 scientific papers dealing with its biology, ecology, management, and impacts as a weed.

Waterhyacinth has been in California for at least one hundred years (Bock 1968). It is 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 applied 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 from waterhyacinth in tropical regions. 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 currently managed with applications of 2,4-D, diquat, or glyphosate. Madsen et al. (1995) demonstrated that commonly used herbicides were more effective at reducing waterhyacinth growth and survival if applications were made when the plants were small (< 45 cm tall) and in the invasion-colonization phase of their life cycle. Previous studies of waterhyacinth phenology in North America have been conducted in the southern United States (Center and Spencer 1981, Luu and Getsinger 1990, Madsen 1993) and the results may not be directly transferable to populations growing in the Delta due to differences in climate and nutrient availability.

Predictions of plant development have been successfully based on the accumulation of heat units or degree-days (Frank and Ries 1990, Fidanza et al. 1996). Degree-days are the accumulated product of time and temperature between the developmental thresholds for each day. One degree-day is one day (24 hours) with the temperature above the lower developmental threshold by one degree. For instance, if the lower developmental threshold for an organism is 15°C and the temperature remains 16°C (or 1 degree above the lower developmental threshold) for 24 hours, one degree-day is accumulated.

The objective of this study was to 1) characterize the phenology of waterhyacinth growing in the Delta, 2) develop a predictive equation relating waterhyacinth growth to accumulated degree-days for this system, and 3) identify the period when chemical applications would likely be most effective. The ability to predict weed growth and phenology is central to expanding integrated management approaches (Wilen et al. 1996) for invasive plants and may enhance overall understanding of plant phenological patterns (Rathcke and Lacey 1985).

MATERIALS AND METHODS

Waterhyacinth plants growing in Whiskey Slough (at a site northeast of the intersection of California Highway 4 and Bacon Island Road at approximately 37°56'N, 121°22'W) were sampled at 2 to 3 week intervals beginning November, 1995

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through July, 1997. (The sample site was sprayed with herbicides in July, 1997, effectively ending this study.) On most sampling dates, we collected ten waterhyacinth plants (ramets). However, on a few dates six to nine plants were collected (especially in winter when plants were scarce) and on one date 20 were collected. Plants were returned to the facility at Davis where the following measurements were made: dry weight (55°C for 48 h), height (measured as the distance between the base of the tallest leaf and the top most portion of the lamina), number of green leaves (living leaves), number of brown leaves (dead leaves due to frost exposure), and the width of the largest lamina. Lamina area was calculated from lamina width using the equation for the area of a circle. Lamina area per plant was estimated by multiplying the number of living leaves per plant by the mean lamina area for each sampling date. We also noted the presence or absence of flowers on each sampling date.

Previous estimates of waterhyacinth growth rates in the Delta were based on changes in ramet fresh weight (Bach 1969). Using fresh weights for this purpose is considered unsuitable (Westlake 1963). So in order to compare waterhyacinth growth in the Delta with other systems, we calculated relative growth by regression of the logarithm of plant dry weight versus time for samples collected from May 1 to October 1, 1996.

We calculated degree-days with the single triangle method (Zalom et al. 1983). Several methods are used to estimate degree-days through the use of daily minimum and maximum temperatures. All are approximations of the actual number of degree-days accumulated for a given set of daily temperatures and developmental thresholds, and therefore do not provide the exact degree-day values. However, most are interchangeable considering the accuracy of weather instruments used and the precision required for management decisions (Wilson and Barnett 1983). We used 10 and 40°C as the lower and upper thresholds, respectively based on Gopal (1987, page 136). The calculations were made using University of California Integrated Pest Management System (http://ipm.ucdavis.edu) air temperature data from a site designated as LODI.C which is about 22 km northeast of the study site. The University of California Integrated Pest Management System provides weather data and degree-day based models used in large-scale agricultural pest management at various locations throughout California. However, the University of California Integrated Pest Management System does not provide a model for the growth of waterhyacinth.

We used lamina area per plant as the indicator of seasonal waterhyacinth growth because Center and Spencer (1981) reported that lamina area was a robust indicator of waterhyacinth growth in a Florida lake (Center and Van 1989, Van and Center 1994). Using lamina area per plant during 1996, we calculated the proportion of maximum lamina area per plant on each sampling date by dividing the mean lamina area per plant on that date by the maximum lamina area by the end of the growing season. The relationship between resulting proportions and accumulated degree days was analyzed by logistic regression (SAS Institute, Inc. 1999). We fit the following equation for the 1996 data with accumulated degree-days as the independent variable:

$$\text{Proportion sprouted} = e^{\text{logit}}/(1 + e^{\text{logit}}),$$

where logit = intercept + (coefficient × accumulated degree-days).

We tested the goodness-of-fit of the equation using the test proposed by Hosmer and Lemeshow (SAS Institute, Inc. 1999). We also used the PROBIT procedure in SAS to calculate inverse predictions, to obtain the accumulated degree-days associated with various waterhyacinth growth stages. We also calculated degree-days for 1989 to 1998 and used this information to evaluate the expected variability in predicted stages of waterhyacinth growth.

RESULTS AND DISCUSSION

Waterhyacinth height increased from less than 10 cm in winter and early spring to more than 80 cm in late summer (Figure 1A). During the same period mean plant dry weight increased from 10 g to 85 g (Figure 1B). Mean plant weight and mean plant height were strongly correlated (Pearson correlation coefficient = 0.81, N = 39, $P < 0.0001$). The number of dead leaves per plant (caused by frost damage) was greatest in the winter and declined through June. (Differentiating dead from living leaves allowed for accurate assessment of laminar area per plant. Since the dead leaves do not immediately disappear from the plant, only counting the number of leaves would overestimate laminar area and would not clearly show the period of new leaf emergence in spring.) New leaves started to appear in March. From June through mid-September green leaves were present (Figure 1D). Beginning in March, lamina area per plant increased through October (Figure 1C). Plants with flowers were present on a few plants at the sample site from May 20 to August 12, but they were not abundant. Gopal (1987) stated that waterhyacinth often displays patchy flowering, i.e., a small patch of plants in a stand will flower while other plants in the stand do not. A similar pattern was observed for plants in the Delta.

Waterhyacinth RGR for the entire 1996 growing season (May to October) for 1997 (May to July) are given in Table 1. The higher value in 1997 was probably due to using a reduced data set from May to July instead of to October. The 1996 value is similar to 1.50% day^{1} reported by Center and Spencer (1981) for waterhyacinth growing in Lake Alice, Florida.

Parameters for a logistic regression equation relating growth, as relative lamina area per plant, to accumulated degree-days for 1996 are given in Table 2. We judged the equation as adequate based on visual inspection (Figure 2), and the results of the Hosmer and Lemeshow Test (Chi-Square = 1.52, DF = 7, P = 0.98).

The degree-day equation was solved for the number of degree-days required for various proportions of maximum growth. Table 3 illustrates the variation in dates when 5, 20, or 50% of waterhyacinth growth would be expected. For the ten-year period, 1980-1989, the mean date for accumulating 382 degree days (associated with 5% of maximum waterhyacinth growth) was May 10, but there was noticeable year to year variation (Table 3). Similarly the mean date for accumulating 869 degree days or 20% of maximum lamina area was June 30. These results also indicate that on average waterhyacinths would have attained 50% of their maximum leaf area by August 7. These data imply that waterhyacinth plants in the Delta would be most susceptible to herbicide treatments

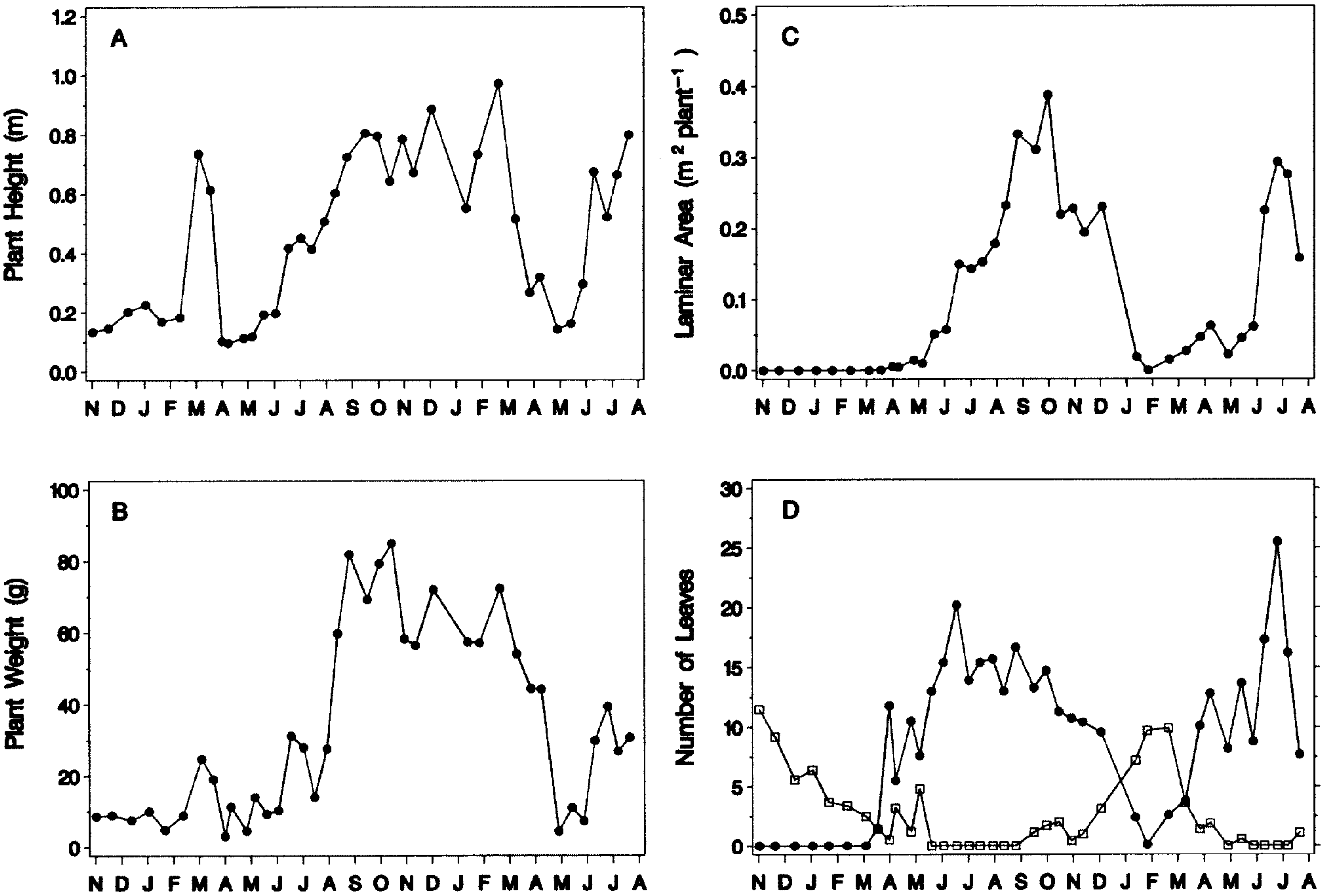

Figure 1. Characteristics of waterhyacinth collected from the Sacramento/San Joaquin Delta from 1995 to 1997. Values plotted are the mean of six to twenty plants, but on most dates ten plants were collected. In 1D, the open boxes represent the number of dead leaves (defined as brown leaves, likely due to frost damage).

(i.e., less than 25% of maximum size) between May 10 and June 30 (Madsen et al. 1995). Treatments applied after that time may be less efficacious.

Seasonal growth for waterhyacinth in the Delta reached peak values in October. This differs from previous reports from field studies. Center and Spencer (1981) measured

TABLE 1. REGRESSION ANALYSES YIELDING RELATIVE GROWTH RATES (= THE SLOPE) BASED ON TOTAL DRY WEIGHT FOR WATERHYACINTH DURING THE GROWING SEASON IN 1996 (MAY 6 TO SEPTEMBER 30) AND 1997 (APRIL 28 TO JULY 21). UNITS ARE DAY^{-1} (I.E., $G\ G^{-1}\ DAY^{-1}$).

Year	Regression Equation	Pr > F	R^2	N
1996	Log DW (g) = -197.54 + 0.0151 × day	0.0003	0.78	11
1997	Log DW (g) = -326.77 + 0.0241 × day	0.0143	0.73	7

TABLE 2. ANALYSIS OF MAXIMUM LIKELIHOOD ESTIMATES FOR LOGISTIC REGRESSION OF PROPORTION OF MAXIMUM LAMINA AREA PER PLANT VERSUS ACCUMULATED DEGREE-DAYS (ADD) FOR WATERHYACINTH IN THE SACRAMENTO/SAN JOAQUIN DELTA. INTERCEPT AND SLOPE ARE USED TO ESTIMATE LOGIT FROM THE EQUATION, LOGIT = INTERCEPT + SLOPE * ACCUMULATED DEGREE-DAYS. THE PROPORTION OF MAXIMUM LAMINA AREA IS THEN ESTIMATED USING THE EQUATION, $P = E^{(LOGIT)}/(1 + E^{(LOGIT)})$. WALD CHI-SQUARE AND ITS PROBABILITY TEST THE NULL HYPOTHESIS THAT THE PARAMETER DOES NOT DIFFER FROM ZERO.

Parameter	DF	Estimate	Standard Error	Wald Chi-Square	Pr > Chi-Square
Intercept	1	-4.1654	0.9188	20.55	<0.0001
Slope	1	0.00319	0.0008	17.62	<0.0001

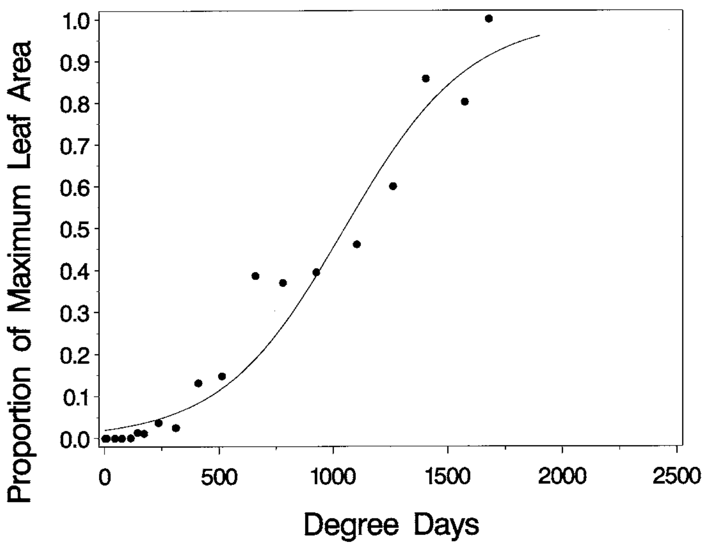

Figure 2. Growth of waterhyacinth during 1996 was related to accumulated degree-days. Solid dots represent observed data and the solid line represents the logistic equation relating relative lamina area per plant to accumulated degree-days given in Table 2.

waterhyacinth growing in Lake Alice, Florida. They reported that standing crop peaked in mid-June and gradually declined thereafter. Luu and Getsinger (1990) reported that maximum biomass occurred in early to mid-September for waterhyacinth grown in outdoor cultures at Vicksburg, Mississippi. Differences between these reports and the Delta waterhyacinth may be due to latitudinal changes in climate.

While it has been recognized that temperature is an important determinant of plant growth (Frank and Ries 1990; Fidanza et al. 1996), to our knowledge this is the first attempt to describe the growth of waterhyacinth as a function of degree-days. Equations derived in this study fit the data well, and provide a means of predicting the temporally distinct pattern of growth (i.e., change in lamina area per plant) observed during the one-year period of this study. This was likely due to the incorporation of both lower (10°C) and upper (40°C) thresholds into the calculation of degree-days.

Table 3. Dates associated with selected growth stages of waterhyacinth (defined as % of maximum lamina area per plant) during a ten year period. Dates estimated from logistic regression equation relating lamina area per plant to accumulated degree-days using daily minimum and maximum temperatures from the UC IMPACT system for Lodi, California.

	Date for 5%	Date for 20%	Date for 50%
1989	May 4	July 2	August 9
1990	April 29	June 29	August 4
1991	May 21	July 10	August 15
1992	May 4	June 21	July 28
1993	May 3	June 26	July 31
1994	May 11	July 4	August 10
1995	May 4	July 4	August 6
1996	May 3	June 19	July 26
1997	April 28	June 17	July 26
1998	May 28	July 18	August 21
Earliest	April 28	June 17	July 26
Latest	May 28	July 18	August 21
Average	May 10	June 30	August 7

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