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EVALUATION OF VEGETATION MANAGEMENT STRATEGIES FOR CONTROLLING MOSQUITOES IN A SOUTHERN CALIFORNIA CONSTRUCTED WETLAND

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ABSTRACT. The abundance of mosquito larvae and adult production were measured in 3 vegetation treatments and 2 species of emergent macrophytes in replicated wetland mesocosms (12 × 80 m). During the 8-wk study, no significant differences were found in abundances of larvae and emerging adult mosquitoes among the vegetation treatments: 100% of the surface area in emergent vegetation, 50% of the surface area in emergent vegetation in 5-m-wide rows, and 50% of the surface area in emergent vegetation in 10-m-wide rows. Mosquito larvae (predominantly *Culex tarsalis* and *Anopheles hermsi*) were significantly more abundant in inundated bulrush (*Schoenoplectus californicus*) than in inundated cattail (*Typha* sp.). Adult emergence from vegetated zones containing bulrush also was significantly greater than from cattail. The failure of reduced emergent vegetation coverage to provide a significant reduction in mosquito production from the vegetated zones of the wetlands might have been caused by favorable conditions for mosquito oviposition and larval development after vegetation management and by the ineffectiveness of mosquito predators in emergent vegetation. A 50% reduction of vegetation did not significantly reduce the water quality of the wetland effluent; however, narrower rows (<5 m wide) of vegetation may be required to reduce mosquito production from vegetated regions of the treatment wetlands. Even though the abundance of mosquito larvae in open water is typically less than in emergent vegetation, creation of open-water zones in shallow treatment wetlands (<1 m depth) by drying the wetland followed by removal of emergent vegetation with heavy equipment is unlikely to provide a significant long-term reduction of mosquito production.

KEY WORDS Mosquitoes, *Anopheles, Culex,* constructed treatment wetland, bulrush, *Typha*

INTRODUCTION

In the arid southwestern United States, an increasing human population will require an increase in the water supply and wastewater treatment. Constructed treatment wetlands may provide a cost-effective alternative to conventional wastewater treatment facilities. In addition to lower costs for construction, operation, and maintenance relative to conventional wastewater treatment systems (Kadlec and Knight 1996), constructed wetlands also may provide many other important functions provided by natural wetlands, such as biodiversity conservation, flood control, and recreation. Wetland treatment systems have taken their place among the proven technologies available for protecting surface-water quality and now are being used worldwide to improve water quality from a multitude of different pollution sources (Kadlec and Knight 1996).

One drawback to constructed treatment wetlands containing dense stands of emergent vegetation is that they may encourage the proliferation of pestiferous and pathogen-vectoring mosquitoes. By reducing water flow, vegetation provides shelter from the current and other physical disturbances, thus creating ideal larval mosquito habitat. Vegetation increases food resources for larval mosquitoes (e.g., algae, protozoa, bacteria, and organic detritus) (Clements 1992) by providing a substrate for attachment and a source of carbon. Vegetation also may provide refuge from predators (e.g., Notonectidae and *Gambusia*) by decreasing predator vision and movement with increasing distance into dense stands of vegetation. Increases in vegetation coverage have been shown to reduce predation pressure of mosquitofish (Orr and Resh 1987, Berkelhamer and Bradley 1989), and abundance of mosquito larvae has been positively correlated to vegetation density (Walton and Mulla 1991, de Szalay and Resh 2000).

The percentage of wetland surface area supporting emergent vegetation and the species of emergent vegetation is thought to influence mosquito production. A hemimarsh configuration (50% vegetation coverage) has been found to improve habitat quality and increase food supplies for waterfowl (Murkin et al. 1982, Batzer and Resh 1992, de Szalay and Resh 1997) and also reduce mosquito production relative to that in fully vegetated wetlands (Thullen et al. 2002). Vegetation coverage should not exceed 50% of wetland surface and vegetation should be restricted to small stands (MVCAC 1997). Stands of vegetation 28 m^2 in size may be small enough to reduce mosquito production (MVCAC 1997), but patches of vegetation may need to be as narrow as 1 m wide to limit mosquito production (Collins and Resh 1989).

Plant species also can affect mosquito abundance. Collins and Resh (1989) evaluated the mosquito production propensity of wetland plant species based on 4 factors: intersection line value, crayfish food value, waterfowl food value, and fish obstruction value. Ironically, the 3 most widely used plant genera in constructed treatment wetlands are *Schoenoplectus* (bulrush), *Typha* (cattails), and

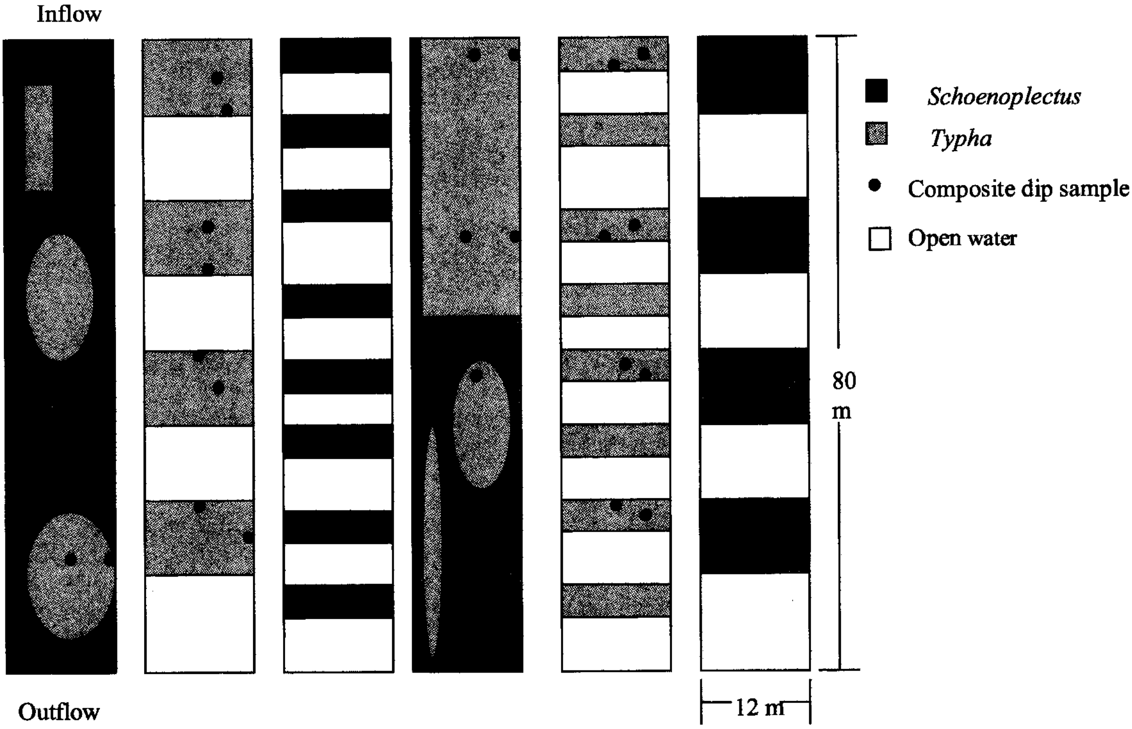

Fig. 1. Schematic representation of the position of dip samples in the 6 research cells at Prado Wetlands, Corona, CA.

Phragmites (reed), all of which have a comparatively high propensity for mosquito production. However, the mosquito production propensity scores are hypothetical, and quantitative experiments have not been done to test different plant species in different habitats.

In this study, we examined the effects of vegetation distribution and macrophyte species on mosquito abundance and water quality in replicate constructed treatment wetlands. We hypothesized that vegetation coverage in a few wide rows would provide more refuge, and thus produce more mosquitoes, than the same vegetative surface area coverage in a greater number of narrower rows. We also evaluated the effect plant species had on mosquito abundance by comparing mesocosms containing cattail vs. mesocosms containing California bulrush (*Schoenoplectus californicus* (Meyer) Sojak).

MATERIALS AND METHODS

The study site was the Prado Wetland near Corona (Riverside County), CA. The Prado Wetland is a 180-ha constructed wetland that serves to remove nitrates and other pollutants from the Santa Ana River before recharging an underground aquifer. Six wetland research cells (12 × 80 m) located near the inlet of the large wetland were used during this study. Two research cells contained predominantly California bulrush, 2 contained predominantly cattails (*Typha* sp.), and the remaining 2 contained a mixture of bulrush and cattails. Each vegetation treatment (100% of the surface area in emergent vegetation, 50% of the surface area in emergent vegetation in 5-m-wide rows, and 50% of the surface area in emergent vegetation in 10-m-wide rows) was randomly assigned to 2 research cells (Fig. 1). Before modification, each research cell was completely covered by vegetation that had not been manipulated for 5 years. All research cells were drained and dried for approximately 1 wk, and a large backhoe was used to remove vegetation from the designated research cells corresponding to each treatment. Vegetation was removed by dredging the substrate to a depth of approximately 0.12 m; the research cells were not deepened appreciably. The cells were flooded on July 14, 1999.

Mosquito larvae were collected weekly from each cell from July 22 until September 16. Eight composite dip samples (3 dip samples taken along a 6-m transect per sample) were taken from each research cell by using a 350-ml dipper (Fig. 1). The 3 dips were combined in a concentrator cup (mesh aperture 200 μm) and preserved at a final concentration of approximately 50% ethyl alcohol. All dip samples were obtained by the same individual throughout the entire study to reduce experimental error due to differences in sampling technique. All mosquito larvae were identified to genera and 3rd and 4th instars were identified to species by using Meyer and Durso (1998).

The adult mosquitoes emerging from the research cells were monitored with emergence traps weekly from July 30 until September 30. Six 0.25-m^2 emergence traps (Walton et al. 1999b) were placed adjacent to the dip transects in each research cell: 2 were placed near the inlet, 2 were placed in the middle of the research cell, and 2 were situated near the outlet. At each position, 1 emergence trap was placed at the edge of the vegetation and 1 was placed 2.5–5 m into the vegetation (Fig. 1). The emergent vegetation was clipped just above the water surface so the trap would rest above the vegetation.

Emerging mosquitoes collected after 4 days were euthanized and enumerated to species by using Meyer and Durso (1998). The traps were removed from the water for 3 days between collections to prevent colonization by larval chironomids. A small strip (5 mm × 20 mm) of Hercon Vaportape II (10% 2,2-dichlorovinyl dimethyl phosphate and 0.75% related compounds; Hercon, Emigsville, PA) was placed into each collection jar. We found this necessary because Argentine ants (*Linepithema humile* (Mayr)) had almost completely emptied the collection jars during the 1st week in which emergence traps were deployed.

Nitrate-nitrogen (NO_3-N) and ammonium-nitrogen (NH_4-N) were measured at the inflow and outflow of each research cell on August 18, August 27, and September 9. Water was supplied from a common equalization pond to each research cell through a drop box. Water samples (100 ml) were preserved in the field with 1.5 ml of 2 N H_2SO_4. Samples were analyzed for NO_3-N and NH_4-N by using colorimetric methods with a Technicon Autoanalyzer II (Technicon Instruments Corp., Tarrytown, NY).

A 2-way repeated measures analysis of variance (ANOVA) was used to test for differences in the abundance of mosquito larvae and emerging adults between the vegetation species (*Typha* sp. and *S. californicus*) and among the vegetation pattern treatments. The abundance of emerging adults was $\log_{10}(x + 1)$ transformed to normalize the distributions before analyses. Weeks were treated as repeated measures in all analyses.

RESULTS

The abundance of mosquito larvae in research cells containing *S. californicus* was significantly greater ($F_{1,2} = 449.4$, $P = 0.002$) than in research cells containing *Typha* sp. (Fig. 2). The 2 predominant mosquito species collected in dip samples were *Culex tarsalis* Coquillett and *Anopheles hermsi* Barr and Guptavanji. At the beginning of the experiment (July 29), abundance of *Cx. tarsalis* was high in the research cells containing *S. californicus* (>1 larva/dip) but declined quickly to less than 0.5 larva/dip by August 14 (Fig. 2). In research cells containing *Typha* sp., abundance of *Cx. tarsalis* never averaged greater than 0.3 larva/dip. Unlike larval *Cx. tarsalis*, which were not collected after August 19, the abundance of larval *An. hermsi* was comparatively consistent during the entire study, averaging between 0.5 and 2.0 larvae/dip in the research cells containing *S. californicus* and between 0 and 0.5 larva/dip in the research cells containing *Typha* sp. (Fig. 2). The abundances of larval *Cx. tarsalis* ($F_{1,2} = 32.2$, $P = 0.030$) and larval *An. hermsi* ($F_{1,2} = 103.2$, $P = 0.010$) in the research cells containing *S. californicus* were significantly greater than in the research cells containing *Typha* sp.

Emergence of adult mosquitoes (i.e., all species) from the research cells containing *S. californicus* also was greater than from cells containing *Typha* sp. (Fig. 3); however, the difference was only statistically different at the $\alpha < 0.10$ level ($F_{1,2} = 12.061$, $P = 0.074$). The number of emerging *Cx. tarsalis* increased rapidly in the research cells containing *S. californicus* to 10/m^2/day by August 10 and then decreased to an average of about 3/m^2/day on August 17 (Fig. 3). *Culex tarsalis* emerging from research cells containing *Typha* sp. showed the same population trends, increasing to 2/m^2/day on August 10 then declining. No adult *Cx. tarsalis* were collected emerging from either treatment after August 23. Emergence of *Cx. tarsalis* was not significantly different between the 2 plant species ($F_{1,2} = 0.802$, $P = 0.465$).

Emergence of adult *An. hermsi* was relatively consistent throughout the study. Research cells containing *S. californicus* averaged 1 emerging *An. hermsi* per square meter per day, whereas research cells containing *Typha* sp. on average produced fewer than 0.5 emerging *An. hermsi* per square meter per day (Fig. 3). The abundance of emerging adult *An. hermsi* from the research cells containing *S. californicus* was significantly greater than the abundance of *An. hermsi* emerging from the research cells containing *Typha* sp. ($F_{1,2} = 65.73$, $P = 0.015$).

The abundance of mosquito larvae did not differ significantly among the 3 vegetation pattern treatments ($F_{2,3} = 0.561$, $P = 0.621$). Research cells with 50% vegetation cover (5-m- or 10-m-wide rows) averaged slightly greater abundance (2–3 larvae/dip) than the fully vegetated research cells (<1 larva/dip) during the 1st 2 wk, but no marked differences were found in mosquito abundance among the 3 treatments for the remainder of the study (Fig. 4). Each mosquito species and total larval mosquito abundance did not differ significantly among the treatments (repeated measures ANOVAs, $P > 0.05$).

Emergence of *Cx. tarsalis* was slightly greater from the 10-m treatment during the initial 3 wk of the experiment (Fig. 5), but no significant differences existed among the vegetation pattern treatments (repeated measures ANOVAs, $P > 0.05$).

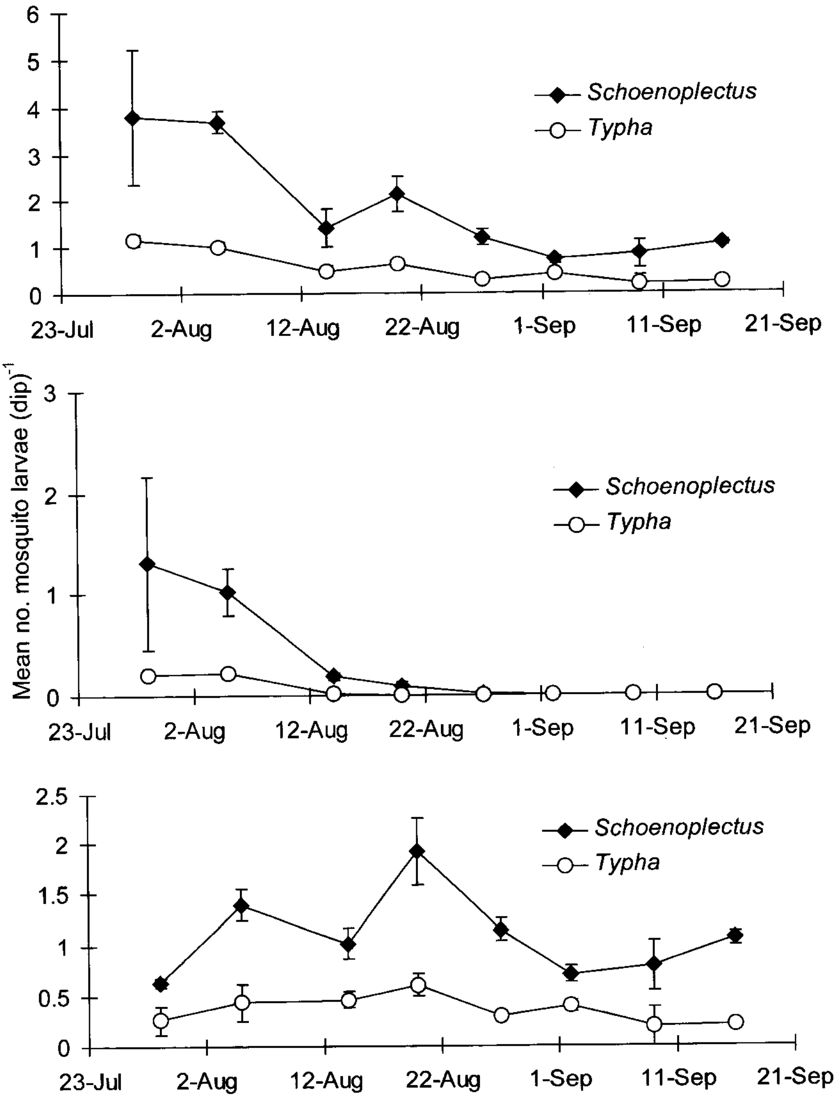

Fig. 2. Abundance (mean ± SE) of mosquito larvae collected in dip samples from research cells containing *Typha* sp. or *Schoenoplectus californicus* at Prado Wetlands, 1999. (Top) All mosquito larvae. (Middle) Third and 4th instar *Culex tarsalis.* (Bottom) Third and 4th instar *Anopheles hermsi.*

Also, no significant difference was found in total adult mosquito emergence among the 3 vegetation pattern treatments ($F_{2,3}$ = 0.463, P = 0.668).

Five mosquito species were collected emerging from the research cells: *Cx. tarsalis, Culex quinquefasciatus* Say, *Culex erythrothorax* Dyar, *Culex stigmatosoma* Dyar, and *An. hermsi.* In addition to these species, 9 larval *Culex restuans* Theobald were collected in dip samples. The relative abundance of each mosquito species collected emerging from the wetland varied temporally (Fig. 6). In all treatments, the abundance of *Culex* spp., predominantly *Cx. tarsalis,* increased rapidly during the 1st 2 wk then declined and *Culex* spp. almost completely disappeared by August 30. After August 30, *An. hermsi* accounted for more than 80% of the emerging mosquitoes.

No significant difference was found in nitrate concentration among the vegetation pattern treatments ($F_{2,3}$ = 1.065, P = 0.447). The mean NO_3-N concentration at the inflow and outflow was 6.65 ± 0.69 mg/liter and 5.92 ± 1.36 mg/liter, respectively. The concentration of NH_4-N entering the research cells was extremely low, at 0.12 mg/liter.

DISCUSSION

Very few studies quantitatively compare mosquito abundance in different species of emergent vegetation. The results of this experiment suggest

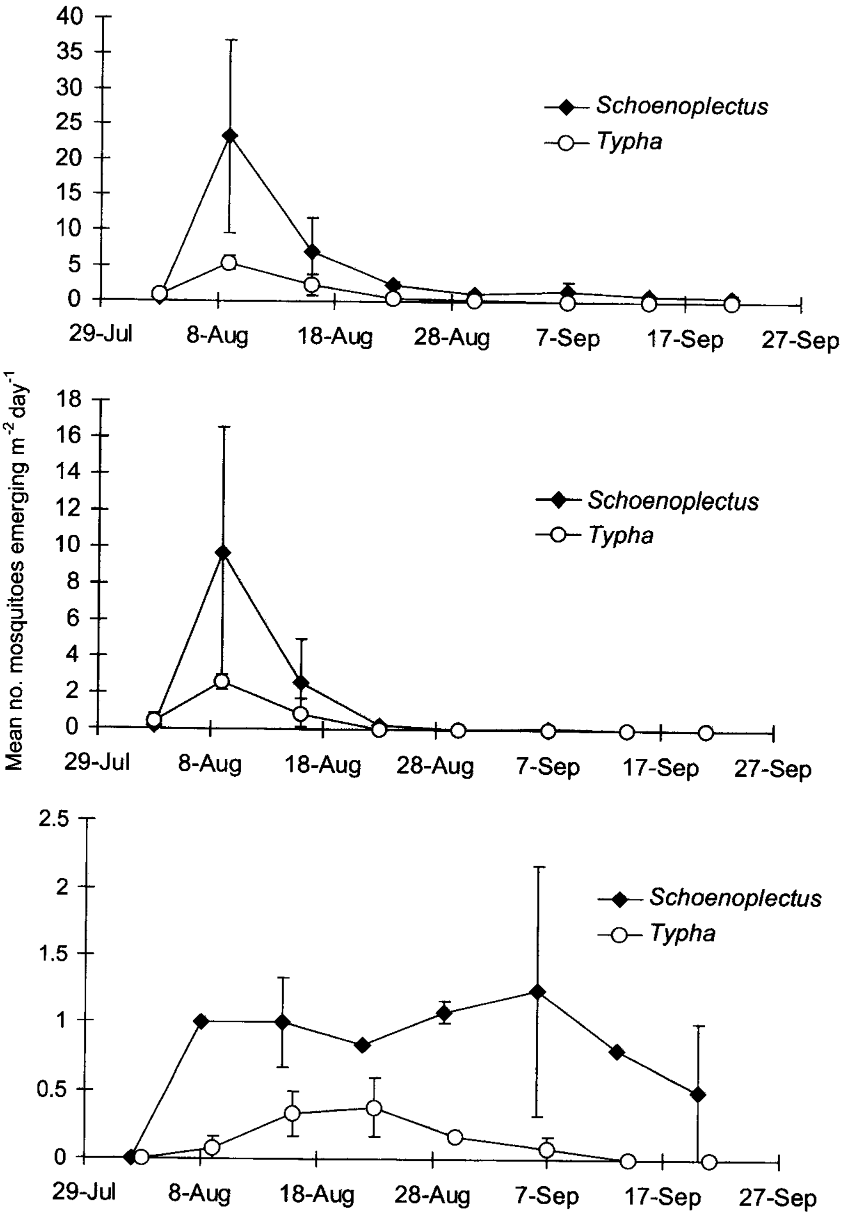

Fig. 3. Abundance (mean ± SE) of adult mosquitoes emerging from research cells containing *Typha* sp. or *Schoenoplectus californicus*. (Top) All mosquitoes. (Middle) *Culex tarsalis*. (Bottom) *Anopheles hermsi*.

that the species of emergent vegetation used in a constructed treatment wetland can have a significant impact on mosquito production and that vegetation management practices that incorporate drying and dredging of shallow (<1-m-deep) treatment wetlands are unlikely to provide significant long-term reductions in mosquito production.

Mosquito abundance differed significantly between the 2 dominant plant species in the Prado Wetland. The abundance of mosquito larvae in and production of emerging adults from research cells containing *S. californicus* were significantly greater than in the research cells containing *Typha* sp. This result was unexpected, because previous estimates suggested that the mosquito production propensity of *Typha* is slightly greater than that of *S. californicus* (= *Scirpus*) (Collins and Resh 1989). A previous study showed mosquito abundance to be positively correlated to root mass and stem densities of *Typha,* but mosquito abundance was not positively correlated to culm density of *Schoenoplectus* when water depth was low enough to expose root masses of *Typha* (Walton et al.1990b). In contrast to the environmental conditions during the study of

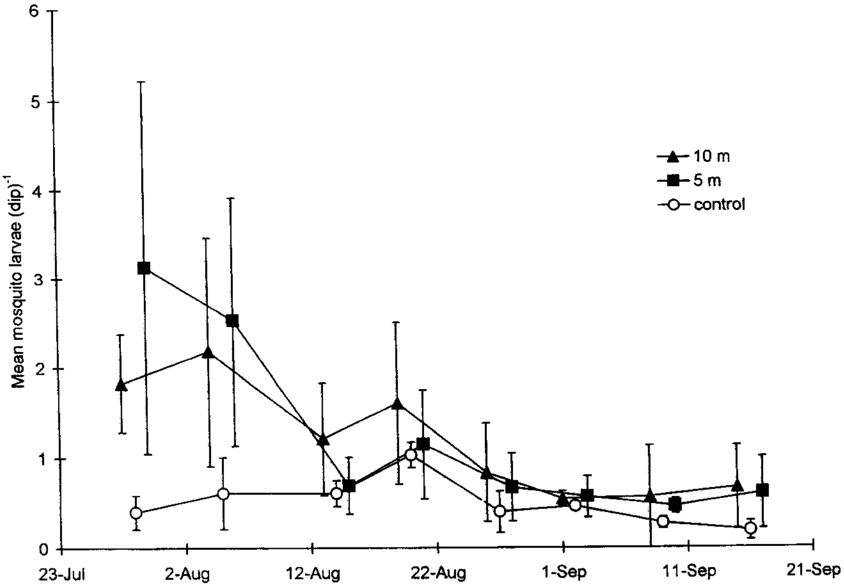

Fig. 4. Abundance (mean ± SE) of mosquito larvae collected in dip samples from research cells with 3 different vegetation pattern treatments at Prado Wetland, Corona, CA. Fifty percent coverage in 5-m vegetated rows is indicated by 5 m; 50% coverage in 10-m vegetated rows is indicated by 10 m; and 100% coverage is indicated by control. Data points are offset to facilitate illustration.

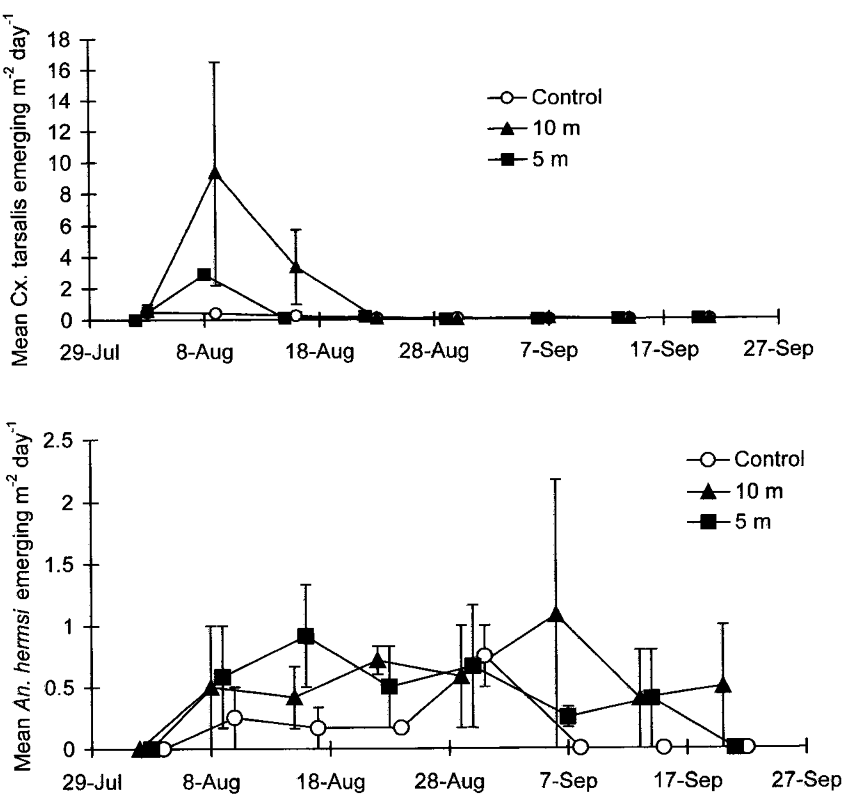

Fig. 5. Abundance (mean ± SE) of adult mosquitoes emerging from research cells that underwent the 3 different vegetation pattern treatments at Prado Wetland, Corona, CA. (Top) *Culex tarsalis.* (Bottom) *Anopheles hermsi.* Data points are offset to facilitate illustration.

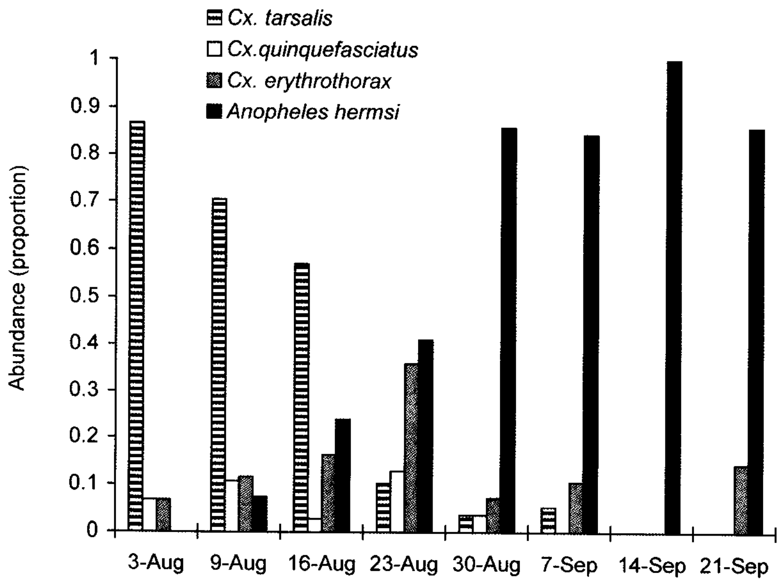

Fig. 6. Relative abundance of mosquitoes collected emerging from the Prado Wetland research cells from August 3 to September 21, 1999.

Walton et al. (1990b), the water depth of the Prado research cells was 0.5 m, leaving no root masses exposed. One plausible reason for the increased mosquito production from bulrush is that *Schoenoplectus* grows in denser stands than does cattail (Kruskal–Wallis $H = 15.747$, $P < 0.001$; bulrush $= 118.9 \pm 64.6$ clumps/m^2, cattail $= 32 \pm 8.2$ clumps/m^2; unpublished data). Dense bulrush stands reduce water flow rate and prevent predator access more than do stands of *Typha.*

Mosquito abundance in vegetated zones of the wetland research cells did not differ significantly among vegetation treatments with either 50% (5-m- or 10-m-wide rows) or 100% surface area coverage by vegetation. Emergent vegetation coverage has been positively correlated with mosquito abundance (Walton et al. 1990a, de Szalay and Resh 2000, Workman and Walton 2000) and mosquito abundance in fully vegetated treatment wetland research cells was expected to be greater than in cells with 50% vegetation coverage. Furthermore, mosquito abundance in research cells with 10-m-wide stands of dense emergent vegetation was expected to be greater than in research cells with narrower 5-m-wide stands of vegetation because wider stands of vegetation were predicted to inhibit predation on mosquito larvae within the vegetation. This result may not have been observed in our study because predators exerted little control over mosquito larvae in the wetland research cells (Jiannino 2001). Naturally occurring piscivorous green sunfish (*Lepomis cyanellus*) kept mosquitofish population size small during this study (Jiannino 2001). Also, the rows of vegetation may not have been narrow enough to allow predators, such as mosquitofish and notonectids, adequate access to mosquito larvae in the vegetation. Collins and Resh (1989) proposed that vegetation stands might need to be as narrow as 1 m wide for predators to maintain mosquito abundance at low levels. However, the cost of maintaining 1-m-wide rows in shallow marshes would be high and probably impractical for large-scale treatment wetlands.

Mosquito abundance in the 50% vegetated wetland research cells was comparatively greater than in the fully vegetated cells during the 3 wk after vegetation management, but thereafter larval mosquito abundance declined to statistically similar levels across the 3 vegetation treatments. Mosquito abundance in the research cells at more than 4 wk after inundation after vegetation management (Fig. 4) was similar to that in established marshes of the Prado Wetland (0.75 larva/dip during July–September 1999) (Keiper et al. 2003), which also contained a mixture of emergent cattails and bulrush. The increased number of larvae during the initial 4 wk of sampling was due to dredging and reflooding of the research cells. Immature stages of *Cx. tarsalis* often peak in abundance soon after habitats are flooded and then decline rapidly (Walton et al. 1990c, Beehler and Mulla 1993, Sanford 2003). The pattern of abundance for the 2 dominant mosquito species, a predominance of larval *Cx. tarsalis* followed by an increasing proportion of larval *An. hermsi* as the ponds age, has been documented in several studies within the Prado Wetland (Keiper et al. 2003, Sanford 2003) and was similar to that observed in Central Valley (California) rice fields (Kramer et al. 1988).

Hemimarsh (50% vegetation coverage) configurations have been recommended for wildlife refuges (Murkin et al. 1982, Batzer and Resh 1992, de Szalay and Resh 1997) and constructed treatment wetlands (Thullen et al. 2002) as a strategy to reduce mosquito production and to achieve other goals such as enhanced wildlife habitat value or water quality improvement. Few mosquitoes are produced in the open-water regions of wetlands (Walton et al. 1999a, Thullen et al. 2002) and increasing the proportion of open-water zones in constructed treatment wetlands is expected to reduce basin-wide mosquito production. The trends of mosquito abundance in the small wetland research cells used here suggest that designing constructed wetlands so that deep open-water zones limit the growth of emergent macrophytes is preferable to routine vegetation management practices that require drying of the wetland followed by removal of emergent vegetation from shallow zones by heavy equipment. After vegetation management, emergent vegetation rapidly recolonizes shallow zones of wetlands (Thullen et al. 2002) and the potential reduction of mosquito abundance provided by increasing the proportion of open water in the research cells was offset by the enhanced mosquito production observed immediately after inundation of the research cells.

In conclusion, vegetation management can have a significant impact on mosquito abundance in a constructed treatment wetland. The results of this study reconfirmed that species of plant used in the constructed treatment wetland may have a large impact on mosquito abundance. Wetland area covered by *S. californicus* appears to produce more mosquitoes than wetland area covered by *Typha* sp., at least in the Prado Wetland research cells. More studies should be done to test these results in other constructed treatment wetlands and widen the survey to include other plant species that could be used in these constructed treatment wetlands. Even though narrower stands of vegetation did not impact mosquito abundance at the Prado Wetland, the reduced size of emergent vegetation patches should be studied in other wetland systems, particularly ones in which the predation pressure on mosquito larvae is greater than at this wetland. The effects of narrower stands of vegetation (i.e., 1 m wide) on mosquito abundance and water quality improvement should be examined because it may enhance our understanding of the complicated interaction between vegetation management and the production of mosquitoes in constructed treatment wetlands.

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