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MOSQUITO CONTROL AND SALT MARSH MANAGEMENT: FACTORS INFLUENCING THE PRESENCE OF *AEDES* LARVAE

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ABSTRACT. The addition of ditches to increase tidal circulation in salt marshes provides effective mosquito control, but economic and environmental factors require accurate determination of potential mosquito-breeding habitats to maximize the efficiency of this process. Stepwise multiple regressions were used to determine which of several physical and biological variables were related to the occurrence and abundance of *Aedes dorsalis* and *Ae. squamiger* larvae that were dip-sampled monthly from 44 ponds in eight San Francisco Bay, CA, salt marshes from August 1981 through June 1982. Most of the variance in the dependent variables (45% of occurrence and 22% of abundance) was accounted for by pond inundation height, i.e. the minimum tidal height required to flood a marsh pond; additional variance was accounted for by pond area (5% of occurrence and 4% of abundance), abundance of the water boatman *Trichocorixa reticulata* (12% of occurrence), and percent cover of emergent vegetation (6% of abundance). Based on these physical and biological characteristics, a flowchart of decision rules can be used to determine whether a given marsh pond should be ditched.

INTRODUCTION

Ditching has been a successful mosquito control technique in salt marsh management since the turn of this century (Smith 1904, Headlee 1936, Ferrigno et al. 1975). Recently, the use of ditches has increased because they provide an inexpensive alternative to insecticides (Telford and Rucker 1973, Provost 1977, Shisler et al. 1979, Resh and Balling 1979, De Bord et al. 1975). By connecting mosquito-breeding ponds to natural tidal channels, ditches alter the hydrological characteristics of the ponds in a manner that eliminates mosquito production. In San Francisco Bay salt marshes, ditches have no adverse impact on many terrestrial components of the marsh, such as arthropod community diversity (Balling and Resh 1982), the density of some arthropod populations (Barnby and Resh 1980), or plant composition and production (Balling and Resh 1983a), but they significantly lower the invertebrate diversity of marsh potholes (Resh and Balling 1983). In addition, Atlantic coast studies have shown that when larger ponds are ditched, waterfowl and shorebird composition and patterns of use are altered (Burger et al. 1977).

To minimize the impact of ditching on aquatic habitats, it is important to restrict ditching to only those ponds that produce significant numbers of mosquitoes. Ferrigno et al. (1975) suggest that this is best done by monitoring potential mosquito-breeding sites and ditching only those that produce mosquitoes. Unfortunately, the number of potential sites often makes monitoring prohibitively expensive. For example, if a monitoring program was undertaken in the 1,145 ha Petaluma Marsh in northern San Francisco Bay (Fig. 1), over 15,000 ponds and potholes would require regular sampling and evaluation.

Mosquito control efforts in San Francisco Bay salt marshes have been directed toward two species, *Aedes dorsalis* (Meigen) and *Ae. squamiger* (Coquillett). The multivoltine *Ae. dorsalis* emerges from tidal salt marshes along the California coast from January through October (Telford 1958). Coastal populations occur almost exclusively in saline water, whereas inland

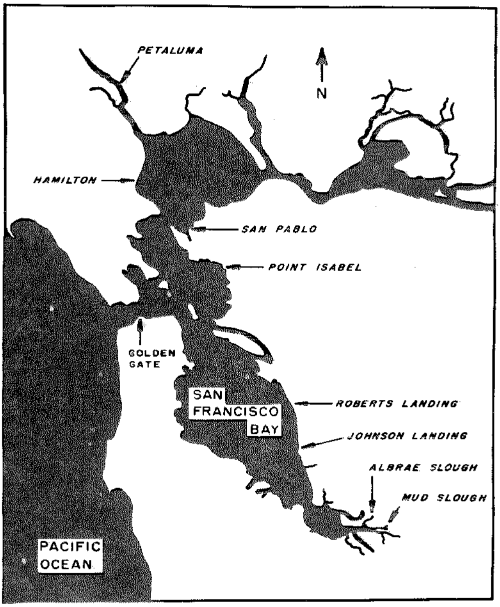

Fig. 1. Map of the San Francisco Bay Area indicating locations of the eight study marshes and the Golden Gate reference station.

populations occur primarily in fresh water (Bohart and Washino 1978). The univoltine *Ae. squamiger* is restricted entirely to salt marshes (Bohart and Washino 1978), and is particularly common in diked marshlands that are subject to winter flooding.

In Pacific coast tidal marshes, *Aedes* production is limited to areas that are inundated only by spring tides (Telford 1958, Provost 1977). However, no study has yet quantified the environmental factors that determine *Ae. dorsalis* and *Ae. squamiger* occurrence within this tidal region. Studies of other *Aedes* species indicate that factors such as flooding-desiccation cycles (Connell 1940), soil moisture (Strickman 1980a), soil salinity (Chapman 1960, Knight 1965, Petersen and Rees 1966, Strickman 1980b), vegetation type (Frohne 1953), and predation pressure (Frohne 1953, Rees 1958) can all influence distribution. This paper quantitatively describes the larval habitats of *Ae. dorsalis* and *Ae. squamiger* in San Francisco Bay salt marshes, and uses this information for developing simple decision rules for determining whether specific ponds should be ditched. When used in a salt marsh management program, this approach can reduce both the cost and the environmental impact of ditching for mosquito control.

MATERIALS AND METHODS

Forty-four unditched sites in eight marshes (Fig. 1) around the San Francisco Bay Area were chosen to provide a broad range of values for each selected environmental variable that might influence the distribution of *Ae. dorsalis* and *Ae. squamiger*. Two types of breeding habitat were included in the study: ponds, which are formed in zones of saturated groundwater, and potholes, which are formed from the blockage of first-order tidal channels. Although differences in the origins of these habitats result in some differences in their physical characteristics, for the purposes of this paper and for mosquito control, both habitat types can be considered the same and will be referred to as ponds.

Several static (i.e. unchanging) variables were measured for each pond: pond inundation height (the minimum tidal height above mean lower low water (MLLW) necessary to inundate the pond, Balling and Resh 1983b), basin area, maximum depth, and percentage cover of emergent vegetation. These variables were measured after the highest spring tides of June 1982, when each of the pond basins was filled.

Several dynamic (i.e. changing) variables were also measured: pond soil salinity, pond water salinity, and relative abundance of both mosquito larvae and the numerically dominant pond invertebrate, the water boatman *Trichocorixa reticulata* Guerin-Meneville (Hemiptera: Corixidae). Pond soil salinities, included because of their possible influence on oviposition (e.g. Petersen and Rees 1966), were measured from 5:1 (by dry weight) distilled-water dilutions of oven-dried (70°C), 6-cm deep soil cores. Although soil salinities vary through the year, we measured them only in late October, when dry-season accumulation of salts in the pond basin was greatest, soil salinity differences between ponds were maximized, and the greatest number of ponds were completely dry. Pond water salinity and abundances of mosquito larvae and *T. reticulata* were measured 4 to 7 days after the highest spring tides of each month from August 1981 through June 1982 (11 sampling dates). Mosquito and *T. reticulata* populations were sampled with a 355 ml dipper; 10 to 40 dips were taken per site, depending on larval density and pond area.

To determine which set of independent variables was the best predictor of mosquito production, stepwise multiple regressions (Zar 1974) were run using two dependent variables: proportion of sampling dates on which larvae occurred (occurrence), and larval abundance averaged over all sampling dates (abundance). Since ditching is considered necessary when either *Ae. dorsalis* or *Ae. squamiger* is present, the occurrence and abundance values were derived from combined counts for both species. Predictor variables tested were area, depth, height, percent cover of emergent vegetation, soil salinity, water salinity, and *T. reticulata* abundance; the last two variables were averaged over all sampling dates.

RESULTS

Aedes larvae were collected in 22 of the 44 ponds sampled. The two species showed a distinct temporal partitioning: *Ae. dorsalis* occurred from March through October with peak abundance in August, whereas *Ae. squamiger* occurred from November through April with peak abundance in January; substantial larval co-occurrence of the two species was restricted to March. These patterns closely match those reported by Telford (1958) in a northern California coastal marsh. The larvae showed no spatial differences since both species occupied the same ponds, even during the period of overlap.

Culiseta inornata (Williston) was the only other species of mosquito collected in the 44 ponds examined. Although Bohart and Washino (1978) reported that *Cs. inornata* is an autumn-winter-spring species in California, we collected it only during March and April, as did Telford (1958). The restriction of this species to early spring in salt marshes may result from a limitation in salinity tolerance, since larvae were found only in water with salinities up to 15 o/oo, a level that is exceeded by most ponds from May through December. In contrast, *Ae. dorsalis* and *Ae. squamiger* were found in water salinities from 2 to 61 o/oo and 2 to 52 o/oo, respectively.

Trichocorixa reticulata was collected on every sampling date in 17 ponds, and at least once in all 44 ponds. Characteristically, the ponds in which we consistently collected *T. reticulata* retained water throughout the year because they were low enough in height to be flooded often, or large enough in volume to withstand long periods without inundation. Combined samples of nymphs and adults, averaged over all ponds, showed that *T. reticulata* reached peak densities in August and September, decreased rapidly in October, and then remained low until late April.

Although fish are abundant in the tidal channels and ditches of San Francisco Bay marshes (Balling et al. 1980), they are seldom observed in the smaller, unditched ponds (Balling 1982).* Apparently, their access is restricted by the thick growth of pickleweed (*Salicornia virginica* L.) that surrounds most of the ponds.

The occurrence of *Aedes* larvae in different ponds was most highly correlated with pond inundation height; 45% of the variance in larval occurrence was accounted for by this factor. Mean relative abundance of *T. reticulata* and pond area accounted for an additional 12% and 5% of the variance, respectively. Addition of the other four variables (soil and water salinity, percentage cover, and pond depth) contributed less than 2% of the remaining variance. Therefore, the optimal regression equation using standardized partial regression coefficients was:

$$\text{Occurrence} = 0.71 \text{ pond height} - 0.31\ T.\ reticulata \text{ abundance} - 0.25 \text{ pond area.} \quad (1)$$

The abundance of *Aedes* larvae was also most highly correlated with pond inundation height; 22% of the variance was accounted for by this factor. Percentage cover of emergent vegetation accounted for an additional 6% of the remaining variance, and pond area accounted for 4%. The addition of all other variables contributed less than 2%. Therefore, the optimal regression equation was:

$$\text{Abundance} = 0.46 \text{ pond height} + 0.22 \text{ percentage cover} - 0.21 \text{ pond area.} \quad (2)$$

DISCUSSION

The regression analyses indicate that the most important correlate of both occurrence and abundance of *Aedes* larvae in the 44 salt marsh ponds examined is pond inundation height. In addition, there is a minimum height below which mosquito production ceases (Fig. 2). This height, which we will refer to as the mosquito production threshold, is approximately 162 cm above MLLW for San Francisco Bay marshes. Approximately 38% of all high tides exceed this height through the year. The overlap of mosquito-producing and non-producing ponds (from 162 to 172 cm, Fig. 2) is a product of the broad regional coverage of our study; this overlap is removed when data from any one marsh are considered. The value of 162 cm for the mosquito production threshold is also specific to the tidal range (MHHW − MHW = 174 cm at the Golden Gate reference station) of our study sites in the San Francisco Bay. For regions with different tidal ranges, we would estimate that the mosquito production threshold would be halfway between MHW

* Balling, S. S. 1982. The influence of mosquito control recirculation ditches on aspects of San Francisco Bay salt marsh arthropod communities. Unpublished Ph.D. Dissertation. University of California, Berkeley. 292 pp.

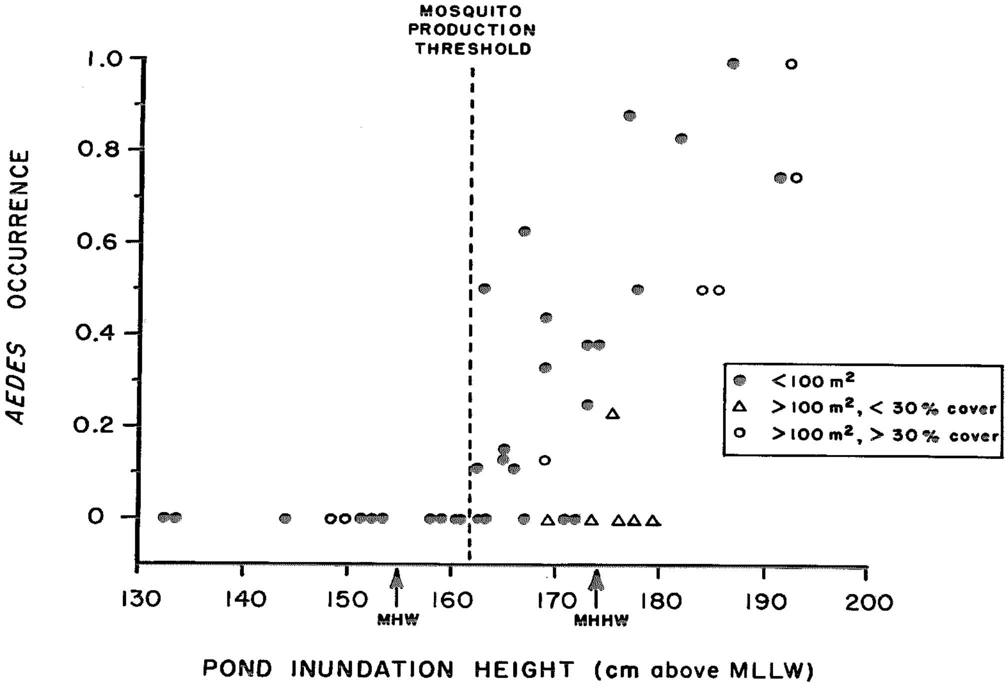

Fig. 2. Comparison between larval *Aedes* occurrence (as a proportion of all sampling dates) and pond inundation height for 44 ponds in eight San Francisco Bay Area salt marshes.

(mean high water) and MHHW (mean higher high water) (Fig. 2).

The determination of pond height to delineate which ponds are mosquito habitats is apparently unnecessary in Atlantic coast marshes because of the well-defined and consistent patterns of vegetational zonation found there. Zones containing *Spartina patens* (Aiten) Muhl. or a mixture of *S. patens* and short-form *Spartina alterniflora* Loisel. are indicative of irregularly flooded mosquito-producing areas (Ferrigno et al. 1975, Provost 1977; W. M. Meredith, personal communication); such areas can be reliably identified and subsequently ditched. In contrast, vegetational zones in the salt marshes around San Francisco Bay are characterized by extensive areas of overlap because of the heterogeneous influences of freshwater inflow around this estuary (Atwater et al. 1979).

Pond area is negatively correlated with mosquito production in the regression equations, although the significance of this relationship is diminished when the cover of emergent vegetation increases. Six ponds greater than 100 m² in surface area and with less than 30% cover are noted separately in Fig. 2 (open triangles), and although the inundation heights of these six ponds indicate that they should produce mosquitoes, larvae were collected in only one of them. In contrast, larvae were collected in 5 of 7 ponds that were greater than 100 m² and had greater than 30% cover (Fig. 2, open circles); the two non-producing ponds were below the mosquito production threshold. Apparently, large ponds that grade into the surrounding vegetation often have margins that become sufficiently dry for *Aedes* oviposition. Once refilled, such pond margins are also protected from wind-generated waves that interfere with the respiration of surface-breathing mosquito larvae. The importance of emergent vegetation as cover for mosquito larvae is further emphasized by the significant, positive relationship between percentage cover and mosquito abundance in regression equation (2).

Abundance of *Trichocorixa reticulata* was inversely related to mosquito occurrence but not to mosquito abundance. Although many corixids are known to be predators (Jansson and Scudder 1972), and at least one species has been credited with reducing mosquito populations (Sailer and Lienk 1954), *T. reticulata* is primarily a bottom feeder that rarely takes mosquito larvae as prey. In fact, the observed inverse correlation is not a predator-prey relationship, but rather the result of contrasting habitat requirements. *Aedes dorsalis* and *Ae. squamiger* have drought-resistant eggs, which allow them to exploit temporary ponds, whereas *T. reticulata* has no drought-resistant life stage and is generally restricted to permanent ponds (Balling 1982).* It follows, therefore, that the absence of *T. reticulata* from a pond, or the presence of mostly recolonizing adults, would indicate that the pond has recently dried up and is likely to be a mosquito-breeding site.

Although pond depth is significantly correlated with mosquito occurrence ($r = 0.47$, $p = 0.001$) and abundance ($r = 0.34$, $p = 0.023$), it was not an important factor in either equation (1) or (2). Rather than reflecting any biological relationship, the significant correlation of depth with mosquito production is presumably due to its correlation with pond inundation height ($r = 0.68$, $p = <0.001$), a relationship also described by Lesser et al. (1977). Pond depth is undoubtedly important to mosquito production when ponds are so shallow that they dry up before adults emerge, but our samples were taken too early (4–7 days after inundation) in the desiccation cycle to detect whether such a relationship existed in the ponds we examined.

Pond water salinity was unrelated to mosquito occurrence or abundance, and this agrees with the conclusions of Connell (1940) and Telford (1958). Petersen and Rees (1966) suggested that the impact of salinity on *Aedes* distribution more likely influences the selection of oviposition sites by females than the survival of the salt-tolerant larvae. However, our measurements of dry-pond soil salinities showed no relationship to mosquito occurrence or abundance. Possibly, the threshold relationship that Petersen and Rees (1966) found for *Aedes* oviposition is subordinate to tidal inundation in salt marsh habitats.

Mosquito-producing ponds located in salt marshes other than the Petaluma Marsh (which is one of the highest marshes in the San Francisco Bay Area) were primarily associated with areas altered by human activities. For example, dikes (which are used to convert tidal marsh to salt evaporation ponds, pasture land, farmland, and waterfowl habitat) can affect neighboring tidal marshes by restricting tidal flow and artificially raising pond inundation heights. This occurs when the weight of the dike displaces and elevates the semifluid marsh. Both changes may sufficiently reduce inundation frequencies to create suitable habitat for salt marsh mosquitoes.

MANAGEMENT APPLICATIONS

A judicious approach to ditching in salt marsh management programs requires an accurate determination of mosquito-breeding habitat. When practical, potential sites should be monitored for the presence of mosquito larvae, since monitoring will give the most definitive information regarding which ponds should be ditched. Such monitoring programs should establish a tolerance level of mosquito abundance above which control measures should be undertaken, because in some cases the discovery of a single mosquito larva has been sufficient justification to ditch a pond, despite the possibility that this larva may have been passively transported into a non-producing pond by inundating tides. In addition, the temporal patchiness of larval distributions suggests that at least one year of regular sampling would be necessary to identify all potential breeding sites in a marsh. During our study, no single sampling date could be used to accurately predict which ponds would produce mosquitoes; of the 22 ponds that produced mosquitoes sometime during the year, less than half contained larvae on any single date.

The use of environmental correlates to predict mosquito distribution is an accurate, cost-effective alternative to monitoring larval populations. As predictive variables, these correlates are best considered in a simple flowchart (Fig. 3). The flowchart indicates that in San Francisco Bay salt marshes, a pond will produce mosquitoes if it is above the mosquito production threshold (162 cm, adjusted to the Golden Gate reference station), and if it is less than 100 m^2 in area. If it is above the threshold and greater than 100 m^2, the pond will produce mosquitoes only if more than 30% of the basin contains emergent vegetation, i.e. if there is sufficient cover. Ponds below the threshold or ponds greater than 100 m^2 with well-defined banks will not produce mosquitoes, and should not be ditched.

When we used these criteria to classify which of our 44 study ponds should be ditched, six ponds that did not produce mosquitoes were classified as "ditch," a 14% (6/44) error rate. A change in the critical values of any of the predictor variables results in a change in the composition of these errors. For example, if the mosquito production threshold is shifted upward to the point halfway between MHW and MHHW, three ponds that produced mosquitoes would be classified as "do not ditch" and

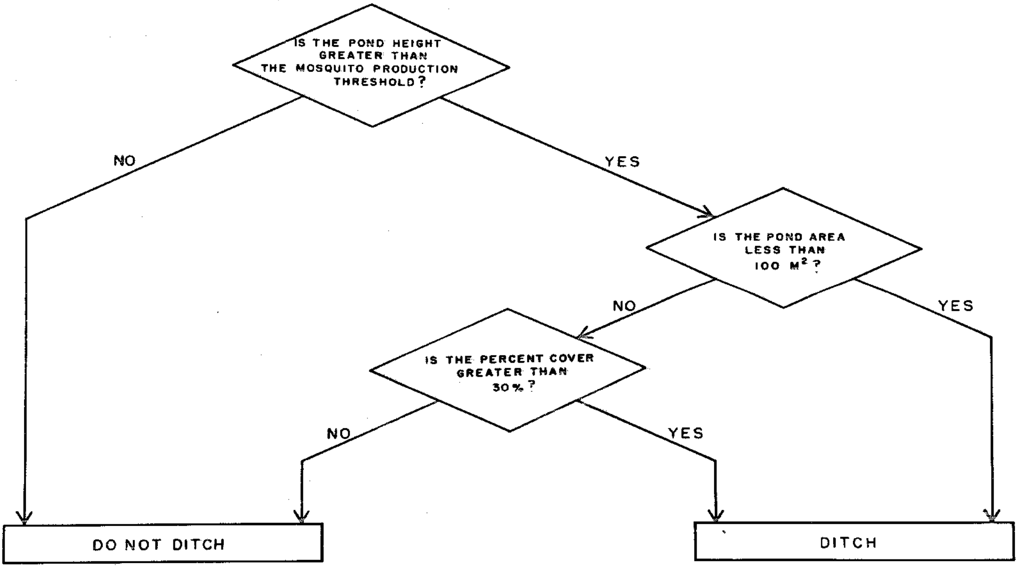

Fig. 3. Flowchart of decision rules for determining whether a pond in a San Francisco Bay salt marsh should be ditched for mosquito control. The mosquito production threshold is the pond inundation height below which mosquito larvae do not occur.

three ponds that did not produce mosquitoes would be classified as "ditch," a 14% error rate. If the mosquito production threshold is shifted upward to 172 cm to guarantee that no non-producing ponds are ditched, then ten mosquito-producing ponds would be classified as "do not ditch," a 23% error rate. Error rates can, of course, be lowered by confining the analysis to a single marsh and eliminating the heterogeneity due to combining several marshes as we did in this study. In contrast to management decisions based on environmental correlates, a decision to ditch all 44 ponds as a precaution against any mosquito production would result in 22 ponds being needlessly ditched, a 50% error rate. Decisions to maximize mosquito control or minimize environmental impact can be used to choose critical values for the predictor variables.

Ditching is a successful method of mosquito control because there is an inundation threshold below which mosquito production does not occur. Although ditches do provide increased access for fish that can prey upon mosquito larvae (Balling et al. 1980), ditching probably succeeds as a control measure because it effectively lowers the pond inundation height to below the height that serves as the mosquito production threshold. As probably occurs in ponds that are naturally below this threshold, frequent tidal inundation keeps the substrate sufficiently wet either to discourage oviposition or to prevent proper conditioning of the eggs. Therefore, to be effective, ditches need not be dug deeper than the depth required to lower the pond inundation height below the mosquito production threshold. Because tidal restrictions on oviposition are undoubtedly present in all salt marsh species of *Aedes*, a management approach based on the determination of a mosquito production threshold has widespread application in the control of salt marsh mosquitoes.

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