SOURCE REDUCTION IN SALT-MARSH MOSQUITO CONTROL: PAST AND FUTURE[1,2]

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ABSTRACT. The history of source reduction for the control of salt-marsh mosquitoes on the Atlantic seaboard is reviewed in the light of its effectiveness, cost and impact on the tideland environment. Those parts of the salt marsh needing ditching or impounding are characterized on the basis of vegetation and of elevation with respect to tides. Source reduction limited to these parts is very effective, and amortization of costs over only a few years makes it more economical than repetitive chemical treatments. New technologies in source reduction will in time convince environmentalists of the merit of these methods of marsh management. Three published papers are singled out for special criticism because of their damaging effects on the achievement of good salt-marsh mosquito control.

INTRODUCTION

Source reduction, or the effort to stop the production of mosquitoes, has always been but one of several mosquito control procedures. In a recent study of pest control and public health for the National Academy of Sciences, we were asked to assess ongoing vector control practices with emphasis on technological problems and alternative techniques. In our charge, "alternative" was not very clearly defined, but in the case of mosquitoes our impression was that it meant alternative to pesticides. As a member of the public health Study Team, one of my assignments was mosquito control, so I made it my first task to place chemical control in its proper context within an average American mosquito control program. Obviously this couldn't be done without putting all other program components, including source reduction, within the same context. I then proceeded to divide the work of organized mosquito control districts, arbitrarily, into 6 broad components: education, preventive planning, surveillance, environmental manipulation, larviciding and adulticiding. A detailed questionnaire, based on this breakdown, was then sent to representative districts across the country. An analysis of the responses, gratefully received, led to the following conclusions, excerpted from the final report (National Academy of Sciences, 1976, p. 63):

"It is clear from this survey that organized mosquito control in the U. S. has always been and continues to be 'integrated control,' in one sense of the term. Although the past 2 decades have seen a notable reliance on the organic insecticides developed since DDT, the mosquito control districts never completely abandoned the many other components of control that have existed since the beginning of organized control efforts. The term 'alternative methods' is misleading if the implication is that the use of insecticides is all there is to mosquito control. There have always been alternatives, in this sense, and what is happening today is only a reordering of the various chemical and nonchemical methods . . . As for the role of organic insecticides now and in the near future, the mosquito control districts of the United States appear to be in accord. The organic insecticides will be useful everywhere into the foreseeable fu-

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[1] Based largely on a report given at the first annual meeting of the Mid-Atlantic Mosquito Control Association, Savannah, GA, March 3, 1976.

[2] Editor's Note: This paper is made available to mosquito control workers who are concerned with salt-marsh management. The author has analyzed a very large number of research reports. His interpretations of research results are useful to those who must defend ditching and diking of valuable wetlands. Any *interpretation* of research results is subject to criticism.

ture, and they will be indispensable in some but not all districts. Wherever the major mosquito nuisance arises from terrain refractory to environmental manipulation for reasons physical, ecological, economic or political, mosquitoes will be controlled with insecticides or they will not be controlled at all."

With this conception of where source reduction and insecticides fit into mosquito control programs, and with the admission that source reduction is not always a viable alternative to chemical control, we can proceed to examine source reduction as a control procedure. Limiting this examination to the grassy salt marshes of the Eastern seaboard of the U. S. is not intended as a slight to source reduction in fresh waters or mangrove swamps. Fresh-water mosquitoes are a very diverse group and their control is correspondingly diversified. By contrast, salt-marsh mosquitoes and their breeding habitat constitute a relatively simple and succinct problem. The mangrove swamps of peninsular Florida are complex and varied habitats.

In the course of this review, three published papers (Bourn and Cottam 1950, DeBord et al. 1975, LaSalle and Knight 1973) are singled out for special criticism because of their deleterious effects on the promotion of good salt-marsh mosquito control.

THE SALT MARSH AND ITS *AEDES* BREEDING

The tidelands of the Atlantic seaboard do not vary greatly in their basic structure (Adams 1963, Miller and Egler 1950), all being grass and rush marshes divisible into a low marsh and a high marsh, conveniently demarked by the mean high water line. The low marsh is everywhere dominated by the tall *Spartina alterniflora* (saltmarsh cordgrass), which at the mean high water line is often supplanted by a short form of the same species or, especially south of Virginia, by the black rush, *Juncus roemerianus*. The true dominants of the high marsh are *Spartina patens* (saltmeadow cordgrass) and *Distichlis spicata* (saltgrass), with frequent wide areas of *Juncus gerardi* (black grass) to the north and of the succulents *Salicornia virginica* (perennial glasswort) and *Batis maritima* (saltwort) to the south. The upland edge of the high marsh and spoil banks are characteristically given over to shrubby admixtures of *Iva frutescens* (marsh elder), *Baccharis halimifolia* (groundsel bush) and *Borrichia frutescens* (sea oxeye) and to the herbaceous composites *Aster tenuifolius* (saltmarsh aster), *Solidago sempervirens* (seaside goldenrod) and *Pluchea camphorata* (saltmarsh fleabane). These mere 13 plant species account for over 95% of salt-marsh cover, which is why the tidelands are comparatively simple habitats, at least floristically.

Tidal mathematics are also quite simple. On the Atlantic coast of the United States the tides are semi-diurnal, which means approximately 720 high tides per year. The mean high water line is therefore where half of these, or 360 per year, reach. Mean spring high water is the average of daily runs of spring high tides, usually totalling 50 a year. Disregarding annual sea level patterns (not safe to do in Florida, *vide* Provost 1973), we may then say that at the mean high water line there are 30 tide floodings per month, and at the mean spring high water line there are 4. It has long been known that the primary factor in demarking tideland biota is the ratio of submergence to emergence relative to tides (Johnson and York 1915, etc.), so it is both logical and convenient to relate plant distributions on the salt marsh to a standard landmark such as mean high water.

An example of the confusion caused by such ambivalent terminology as "regularly" and "irregularly" flooded marsh is the unfortunate debacle in North Carolina where it was assumed that black rush was the prime indicator of irregularly-flooded marsh and therefore of salt-marsh mosquito breeding. Without preliminary incrimination by sampling survey, they proceeded to ditch thousands of acres of *Juncus* marsh. Years later a study of mosquito breeding (LaSalle and Knight 1973) demonstrated little difference between ditched and unditched marsh and also showed clearly that tide floodings on the *Juncus* marsh were too frequent for salt-marsh *Aedes* to breed there. But the use of unnecessarily complicated and misleading statistical analysis on data irrelevant to the issue apparently lulled many readers into believing that ditching salt marsh does not stop mosquito breeding. It is regrettable that the report has been repeatedly misread and misinterpreted as documentary evidence to this effect. I fear that this study is hurting the cause of source reduction on the salt marsh as much as did an earlier study in Delaware by the U. S. Fish and Wildlife Service (Bourn and Cottam 1950) which was also designed on false premises and performed on the inappropriate marsh, and yet is considered a "classic" (Gulf South Research Institute 1977, p. 36) and accepted uncritically everywhere as evidence that mosquito ditching destroys salt marshes (see later).

The life cycles and oviposition habits of salt-marsh *Aedes sollicitans* and *Ae. taeniorhynchus* dictate that good breeding habitat must not be flooded by *more* than 4 tides per month (= two spring tide runs of 2 days each). Salt-marsh breeding terrain is therefore mostly above mean spring high water. In the above-mentioned North Carolina investigation, mean floodings per month on the 5 study areas were between 15.0 and 20.8, so these marshes, ditched or unditched, were obviously not *Aedes* breeding terrain, hence the not surprising conclusion: "Based upon the diverse marsh areas studied, the research reported on here disclosed that the *Juncus* marshes in Carteret County were subject to a high rate of tidal flooding for most of the mosquito season, which presumably accounts for the relatively low level of *Aedes* breeding found to occur" (LaSalle and Knight 1973, p. xiii). It is clear from this and other studies on *Juncus roemerianus* marsh (Fornes and Reimold 1973, Jackson 1952, Kurz and Wagner 1957, Oney 1954, Oosting 1954, Teal 1958) that black rush marsh occurs from well below mean high water to mean spring high water and is therefore an indicator of poor *Aedes* breeding terrain.

I have recently demonstrated that the location of the various tidal datums on the salt marsh is a function of the local mean tide interval, i.e. the height of mean high tide above mean low tide (Provost 1976). Where this interval is 10 ft, for instance, about 30% of the tideland is high marsh, and as the interval diminishes more and more of the salt marsh is high marsh. Where the mean tide interval is less than a foot, over 65% will be high marsh. Another geographical factor dictates that 10 to 35% of the high marsh will be below the mean spring high water line. For source reduction of salt-marsh mosquitoes, therefore, it is not necessary to ditch or impound the entire salt marsh but usually some 20 to 60% of its highest elevations.

Few salt marshes exhibit a continuous, unbroken gradient from open estuarine water to upland edge. Contours are often more like a crazy quilt, with islands of high marsh surrounded by low and areas of low marsh intruding into otherwise solid high marsh. The part of a salt marsh which is above mean spring high water is therefore not necessarily or altogether "upper" in the sense of adjoining upland.

HISTORY OF SOURCE REDUCTION ON THE SALT MARSH

The salt marshes along the Atlantic and Gulf Coasts of the United States have been studied for one purpose or another for many years, but it is only in the past decade or so that their role in the natural ecosystems to which they belong has been elucidated. Most earlier investigations were related to some attempt at marsh management, e.g. mosquito control, production of marsh hay, waterfowl, muskrats, etc. The habitat is usually in such equilibrium that management schemes to further one objective were almost certain to affect adversely some of the other resources and functions of the marsh.

Ditching the salt marsh for mosquito control was first instituted in extensive programs in 1912 in New Jersey, following the pioneer investigations of salt-marsh mosquito biology by Dr. John B. Smith (1904) and his subsequent recommendations for control. In the 1930s, this kind of hand-ditching received a big boost when the federal work projects of the depression years adopted these programs as ready consumers of manpower. By the late thirties, wildlife interests were voicing opposition to the ditching going on in the middle Atlantic states. This culminated in the famous and frequently quoted report (Bourn and Cottam 1950) which contended that mosquito control ditches in the Mispillion River marsh of Delaware "drained" the 500-acre expanse of *Spartina alterniflora* which was then replaced by "shrubby growth of groundsel bush and marsh elder," while the invertebrate populations were decimated. The seriousness of the situation was evident, the authors claimed, "when it is considered that by the end of 1938 some 90 percent, or 562,000 acres, of the total original acreage of tidewater marshland along the Atlantic coast from Maine to Virginia had been ditched" (p. 15) thus implying damage by mosquito control to half a million acres of tidal marsh.

Knowing that *S. alterniflora* is usually flooded twice daily by tides, I was astounded at this claim that open ditches had mysteriously drained a small part of the ocean. Following a hunch, I wrote the U. S. Army Corps of Engineers and learned that the Mispillion River had indeed been dredged in 1933 and 1935, prior to the ditching. There was no mention of either dredging or ground water levels in the Bourn and Cottam report. Dredging a tidal river normally drops the river level, so that an adjoining tidal marsh could suffer enough drying to alter the cordgrass vegetation towards a more "high marsh" situation, with attendant *Aedes* mosquito breeding. A reexamination of the marsh in 1973 found it to be a viable expanse of *S. alterniflora* (Shisler et al. 1975), a restoration probably brought about by the very ditching condemned by Bourn and Cottam. And in another report on the marsh (Lesser et al. 1976), the authors confirmed my early suspicion, viz., that the vegetational changes reported by Bourn and Cottam were probably caused by channel dredging in the adjoining river. But the harm to mosquito control had been done, and the unjust charges are still accepted at face value even by the authors of otherwise excellent books such as, e.g., V. J. Chapman's (1960) "Salt marshes and salt deserts of the world" and D. S. Ranwell's (1972) "Ecology of salt marshes and sand dunes." My own researches in the salt marshes of north Florida long ago convinced me that the hand ditching of the thirties had left virtually no mark on the vegetation, which I ascribed to the verified observation that tide water moving in and out of these ditches had no detectable effect on the ground-water table more than a few feet from the ditch. These had also been the findings of Taylor (1937) on Long Island marshes and Travis et al. (1954) on Florida marshes.

As reported long ago (Daigh et al. 1938), the drainage effect varies with the porosity of soils, and the percolation rate is much higher in the sandier soils of the low marsh than in the more peaty soils of the high marsh, so that the potential for damaging the low marsh is actually greater, provided the mean water level is indeed reduced. For this reason, if for no other, ditches in low marsh should be kept to the absolute minimum necessary to properly treat the high marsh.

Although many early reports on salt-marsh impoundments (Chapman and Ferrigno 1956, Darsie and Springer 1957) demonstrated their effectiveness in controlling the breeding of salt-marsh *Aedes* in the middle Atlantic states, none of the impoundments was constructed for mosquito control purposes. Impoundments for mosquito control in Florida were described by Clements and Rogers (1964). Work began there in 1954 in Brevard Country, spread rapidly through the mid-East coast where Indian River tides were everywhere too small to effectuate good control by ditching, and was virtually completed by 1970, before environmentalists launched concerted efforts to stop it. Many of their objections were valid, but, for the most part, the damage done can still be corrected by installing water-control structures.

After World War II, the control of salt-marsh mosquitoes became overwhelmingly an insecticidal campaign, party because the cost of hand labor for ditching had become prohibitive. But the confrontation with wildlife interests was resumed and was now exacerbated by massive larviciding with DDT and other new organic insecticides. It is now history, but it was excessive use of DDT on a salt marsh in the northeast which brought into being the adversary Environmental Defense Fund, which in due time prevailed on the federal government to ban all use of DDT in this country.

There nevertheless emerged excellent collaborative studies of source reduction (Ferrigno 1961, Ferrigno and Jobbins 1966, Florschutz, 1959, MacNamara 1952 and 1957, Springer 1964). This working together reached a peak in a Symposium on the Coordination of Mosquito Control and Wildlife Management held in the U. S. Department of the Interior offices in Washington, D. C. on April 1–2, 1959 (Springer and Vannote 1961). It was sponsored by the American Mosquito Control Association, the Wildlife Society, the U. S. Fish and Wildlife Service, the U. S. Department of Agriculture and the U. S. Public Health Service. Out of it came the National Mosquito Control—Fish and Wildlife Management Co-ordination Committee, which was soon emulated by similar committees organized at state and regional levels, sponsoring similar symposia and conferences, to this day.

It needs emphasizing that until the mid-sixties, the resolution of environmental problems engendered by mosquito control on the salt marshes was altogether in the direction of assuaging wildlife interests in the same terrain. The above-discussed Bourn and Cottam (1950) report, for instance, although entitled "biological" effects of ditching, was concerned mostly with waterfowl effects and sportsmen's concerns. Nowhere at the time was there any interest in overall functioning of the salt marsh as part of a natural ecosystem. Management for waterfowl production or harvesting, or for muskrat production, for example, are special interest usages and are no more "natural" than impoundments or ditches for mosquito control. But while commendable rapprochement was jelling, research on many unrelated fronts was uncovering the role of salt marshes and estuaries in the production (mostly as nursery rather than spawning grounds) of important food and game fisheries, e.g. shrimp (Gunter et al. 1964, Kutkuhn 1966, Lindner and Anderson 1956), blue crab (Darnell 1959, Van Engel 1958), mullet (Anderson 1958, Kilby 1948), snook (Marshall 1959), weakfish (Tabb 1958), and tarpon (Harrington 1958). And more important still, the sixties were witnessing the discovery of the *total* role of salt marshes, independently of any special interests. The salt-marsh ecosystem was being studied intensively (Daiber 1959, Odum 1961, Odum and Smalley 1959, Teal 1962), and the estuaries were being recognized as detritus ecosystems (Odum 1963) with extraordinary dependence on leaf-fall from the salt marshes. Although this research was all done on cordgrass low marsh, there was some speculation (Provost 1973) that the high marsh might play a similar role in the detritus ecosystem but with different seasonal pulses of nutrient imput. Recent research, however, indicates that the situation is not that simple. Eventually it was shown that the extraordinary net primary productivity of *Spartina alterniflora* (tall form) was due to the energy subsidy it received from daily tidal irrigation (Odum and Manning 1973). This led to speculation as to whether ditching the high marsh, by introducing some of this energy subsidy, might not be increasing its productivity (Cooper 1974). It was later shown (Shisler and Jobbins 1975) that ditching does indeed increase the vegetational biomass of *Spartina alterniflora* marshes wherever it increases the tide regime.

By 1973 the true worth of naturally functioning salt marshes was finally receiving economical assessment, reaching estimates as high as $86,000 per acre (Gosselink et al. 1974) and the days were gone for them to be considered mere wasteland. Today, the several natural functions and gratis contributions of salt-marsh ecosystems are known to include: (1) their primary productivity, (2) their special production of life forms of specific value to man, (3) their furnishing of habitat to endangered biota, (4) their function as nutrient traps and thus purifiers of waters, (5) their production of nutrients for estuaries, (6) their work as absorbers of damaging storm energies, (7) their role as weather modifiers, (8) their contribution of recreational and esthetic values, and (9) their simple preservation of precious water.

This modern ecological view of the salt marsh was first brought to the attention of mosquito-control workers by R. C. Clement (1965) of the National Audubon Society, addressing the New Jersey Mosquito Extermination Association. Again in New Jersey, Delaware and Maryland efforts were quick to surface aimed at modifying mosquito-control management of the salt marshes to least obstruct their ecosystem roles (Bodola 1970, Ferrigno 1970, Ferrigno and Jobbins 1968, Ferrigno et al. 1969, Lynch and Langford 1971, Rockel 1969). The open marsh management systems now proposed, especially by Ferrigno and Jobbins in New Jersey, are certainly the best that have been evolved from all the fine research in the middle Atlantic states. These systems should be applicable to the salt marshes everywhere, with a modicum of modification, to achieve source reduction acceptable to any reasonable environmentalist.

THE FUTURE OF SOURCE REDUCTION IN THE SALT MARSH

Overlooking, for the moment, the environmental or conservation consideration, we can predict that source reduction will continue into the distant future as the appropriate and economical method of combatting salt-marsh mosquitoes it has always been. In those areas where the people concentrate their living and work close to vast expanses of salt marsh it makes no sense to let the mosquitoes breed forever, seeking relief in repetitive chemical treatments. In the same National Academy of Sciences study mentioned earlier, I contacted several mosquito control districts in Florida for special instances where costs of source reduction and larviciding could be compared. It developed that the cost of ditching or impounding salt marsh was recovered, on an average, in two or three years of savings on larviciding alone. In one analysis outstanding for its meticulous accounting of all possible costs, E. John Beidler, summarizing for his Indian River Mosquito Control District, concluded: "From this one can estimate that the 4,265 acres of salt marsh in the district impounded 10 to 15 years ago have already effected a saving of about $500,000 or nearly 2 years of present operating costs" (National Academy of Sciences, 1976, p. 169).

At the risk of appearing to belabor the misuse of mathematics in assessing mosquito control, I must comment on a recent report that purports to prove chemical control more economical than source reduction (DeBord, Carlson and Axtell 1975). I hasten to say that the data assembled for this report, all beautifully presented in the appendix, constitute a tremendous accumulation of valuable information for which all of us in mosquito control are deeply grateful. These data, properly analyzed, prove without equivocation that source reduction has greatly reduced mosquito populations wherever used. Yet by subjecting the data to a phenomenal amount of mathematical juggling based on theoretical or illogical suppositions, the report comes out with the amazing conclusion that chemical control not only reduces mosquito populations more than permanent control but is cheaper as well. In short, costs of "temporary" control, overwhelmingly adulticiding, for 1969–1971, are compared with costs of "permanent" control, including ditching and impounding, for 1966–1971, on the basis of per-night female mosquito (all species) light-trap collections, for 1959–1971, and it is concluded that "temporary control was from 1.4 to 3.5 times as effective, per dollar of expenditure, as permanent control" (p. 53). Not only are completely irrelevant "production" factors worked into pretentiously intricate mathematical formulations, but light-trap data, well known to be difficult of interpretation at best, are not even given the necessary logarithmic treatment (Bidlingmayer 1969, Downing, 1976). The study is a prime example of feeding a computer the wrong bits and coming up with a patent absurdity. Not only the earlier assessment (National Academy of Sciences 1976) but later studies document the well-known greater economies of permanent control. Thus, in New Jersey, open water marsh management, with expenditures appropriately amortized (20 years), costs 4.5 to 50.6 times *less* than larviciding (Hansen et al. 1976), i.e. $5.05 to $63.45 per acre for waterworks vs $14.88 per acre *per year,* larviciding.

Source reduction on the salt marsh, whether it's ditching or impounding, can be done without damaging the marsh's primary natural functions. In the case of diking and flooding, it has been shown (Provost 1968, 1969) that salt marsh under impoundment can be effectively managed for several conservation purposes without permitting it to breed mosquitoes. And seasonal flooding has been demonstrated (Provost 1974) to both control mosquitoes and permit exchange of marsh nutrients and estuarine fauna in a near-natural manner. The Gumbo Island impoundment, described in the latter report, is now in its fifth year of 100% effective management for mosquito control and not even the most drowning-susceptible plants, like perennial glasswort, saltgrass and black mangrove (*Avicennia germinas*), have been perceptibly harmed (Jack Salmela, director of the Brevard Mosquito Control District, personal communication).

As for ditching, especially in the manner of open water marsh management, it is more likely to increase than decrease salt marsh productivity. Even as objective an estuarine ecologist as Arthur W. Cooper of North Carolina State University admits that "the increased edge and tidal penetration may increase productivity and contact with the estuarine waters" (Cooper 1974, p. 97). It has, in actuality, been shown that open water marsh management for mosquito control propels the high marsh toward low-marsh productivity because it (a) increases fiddler crab and isopod densities, (b) decreases *Melampus* densities, and (c) increases *Spartina alterniflora* stem biomass (Shisler and Jobbins 1975). Ferrigno (1970) concludes his broad examination of open water marsh management with these words: "Quality ditching and its evaluation are needed for a number of reasons: (1) With more information being gathered on the importance of the tidal food web to shellfish, fish, wildlife and Man's outdoor recreation, the open character of the marsh with freedom of movements of tides through and over the marsh must be maintained; (2) with the mounting public concern on insecticide use, quality ditching is a worthy substitute for chemicals on valuable tidal marshes; and (3) quality ditching is very good mosquito control without harm to wildlife resources" (Ferrigno 1970, p. 94).

As reassuring as this is, coming from a wildlife biologist, it has to be tempered by the realism expressed by Shisler et al. (1975): "Unquestioning acceptance of the dated conclusions of Bourn and Cottam may lead to a misleading interpretation of the effects of ditching. The consideration of water management as being totally detrimental to the salt-marsh ecosystem may result in the dismissal of valuable and ecologically sound approaches to mosquito control" (p. 277). This is well illustrated in another North Carolina study on non-*Aedes*-breeding *Juncus* marshes (Kuensler and Marshall 1973) which, although uncovering no seriously deleterious effect on productivity (on the contrary, a 5-fold increase in aquatic habitat, with all its accompanying fish and other life), gives as its *first* recommendation a moratorium on mosquito ditching until "it is clearly demonstrated to be effective and economically worthwhile" (p. 4). The study was concerned with the effects of mosquito control ditching on estuarine ecosystems, and very properly did not consider the effectiveness or economics of mosquito ditching. Its first recommendation was clearly based on the very same flawed North Carolina investigations (LaSalle and Knight 1973, DeBord et al. 1975) I have criticized above.

CONCLUSION

One must conclude that because people will not tolerate the salt-marsh mosquito infestations arising from untreated salt marsh, those mosquitoes will continue to be controlled. Economically and ecologically, the method of choice will surely be source reduction. I am certain that the environmental concern which today is so effectively impeding such work in some states will eventually endorse properly-designed marsh management systems everywhere. It will take a lot of research and demonstration, but I believe strongly that this rapprochement, however costly, is inevitable.

I close this review and assessment of source reduction for salt-marsh mosquitoes with yet another quotation, one which concluded a recent report on the state-of-the-art of salt-marsh mosquito control for managers of coastal ecosystems (Provost 1977, p. 671).

"In summary, the control of salt-marsh mosquitoes need not now or hereafter be damaging to the estuarine ecosystem. Although environmental malpractice may still occur and many errors of the past await correction, the means are available to control these mosquitoes with impunity to the environment if only the necessary sophistication and funds are recruited for the purpose. This is particularly reassuring because salt-marsh mosquitoes, which reach extraordinary numbers when allowed to breed, are the least likely of all species to be controlled any time soon by the most environmentally acceptable methods of the future, such as genetic control."

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