Journal of the American Mosquito Control Association, 14(2):137–147, 1998

A GEOGRAPHIC INFORMATION SYSTEM APPROACH TO EVALUATING THE EFFECTS OF THE ENDANGERED SPECIES PROTECTION PROGRAM ON MOSQUITO CONTROL[1,2]

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ABSTRACT. The purpose of this study was to assess what impacts on organized mosquito control the implementation of an Endangered Species Protection Program for the Houston toad might have in Chambers and Harris counties, Texas. The study was also intended to demonstrate the value of using geographic information system (GIS) techniques and methodologies in making such assessments to those in mosquito control who are unfamiliar with GIS and its applications. Using the GIS, Geographical Analysis Support System (GRASS), databases were developed on the habitats and patterns of mosquito control insecticide usage occurring in Chambers and Harris counties. These databases were then employed by means of various utilities associated with GRASS and computer-supported, rule-based reasoning processes to create maps depicting the amount and locations of toad habitat and the areas treated annually with insecticides by districts in Chambers and Harris counties. This map information was then used via other GRASS utilities to identify and depict zones of overlap or coincidence between toad habitat and areas treated with insecticides for mosquito control in the 2 counties. As compared to existing maps for toad habitat, our resulting GIS-generated maps gave more precise, easy-to-use information that could be used to make decisions as to how to protect the toad in the zones of coincidence in each county without causing undue disruption to mosquito control activities in these zones.

KEY WORDS Mosquito control planning, Houston toad, pesticide usage patterns, endangered species, computer mapping, conflict resolution, geographic information systems

INTRODUCTION

The Endangered Species Protection Program (ESPP) administrated by the U.S. Fish and Wildlife Service (USFWS) is designed in part to protect endangered and threatened species of fauna and flora from further adverse effects of pesticides. This program was instituted in response to the Endangered Species Act, which provides for the legal protection of endangered and threatened species and, in the case of pesticidal issues, to the Federal Insecticide, Fungicide, and Rodenticide Act as amended. Implementation of the ESPP has been met with the laborious and complicated tasks of identifying and locating the actual habitats of targeted endangered and threatened species, determining the cause(s) for a given species becoming endangered or threatened, and the development of ways to minimize environmental disturbances causing a species' endangerment without negatively impacting the health, economy, and general well-being of people who live, work, and recreate in the same environments where endangered and threatened species occur.

Geographic information system (GIS) technology and methodology stand to be valuable tools in accomplishing the various tasks associated with implementing the ESPP as it pertains to protecting a given endangered animal or plant species. By definition, the GIS is a computerized mapping system used for the capture, storage, retrieval, and analysis of spatial and descriptive data (Coulson et al. 1987). Using such a system, layers of data concerning the habitat characteristics and requirements of an endangered species can be compared to similar layers of data on the environmental characteristics of a particular geographic region being assessed; and by means of computer-supported, rule-based reasoning processes, maps can be generated depicting the exact locations in the region where the species in question would most likely occur and/or where environmental disturbances exist that could have a detrimental effect on the survival of the species. Geographic information system technology is, thus, ideal for solving problems such as the ones associated with implementing the ESPP, which involve large geographic areas consisting of many different types of interacting components. In this regard, Scott et al. (1987) specifically identify GIS technology as a potentially important tool that can be used to deal with the problems of species extinction.

Mosquito control activities, despite their impor-

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[1] This study was conducted in cooperation with the U.S. Department of Agriculture (USDA), Agricultural Research Service, as part of USDA, Cooperative State Research, Education, and Extension Service (CSREES), Southern Regional Project S-260 involving State Agricultural Experiment Station personnel located in Arkansas, California, Illinois, Louisiana, Mississippi, and Texas.

[2] Opinions contained herein are those of the authors and should not be construed as official or reflecting the views of the U.S. Air Force, USDA, or the Texas Agricultural Experiment Station (TAES). Also, any mention of a commercial or proprietary product in this paper does not constitute a recommendation or endorsement of the product by the U.S. Air Force, USDA, or TAES.

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tance to the protection of human and animal health, can be sources of purposeful environmental disturbances that may place harmful pressure on a threatened or endangered species, especially when certain tactics used against mosquitoes must be applied directly to habitats where such species occur. In such instances, a strategy must be developed whereby mosquito control activities may be continued, but at the same time, the well-being of the endangered or threatened species is preserved. Geographic information system methodology has the potential of being a valuable means for efficiently and effectively developing such strategies.

The current study was conducted to demonstrate to those in mosquito control unfamiliar with GIS how these techniques can be employed to plan alternate mosquito control strategies when an ESPP and a mosquito control program come into potential conflict. The goals of this study were to use GIS techniques to investigate, as a model system, patterns of pesticide usage by organized mosquito control districts in Harris and Chambers counties, Texas, relative to their potential impact on remaining populations of the Houston toad, *Bufo houstonensis* Sanders, in these 2 coastal counties; and to develop a plan whereby the districts could continue to use insecticidal mosquito control tactics if and when an ESPP was implemented in their respective counties for the toad. Specific objectives of the study were to define the probable habitat of the Houston toad in Harris and Chambers counties and to establish a protection zone around these habitat areas; to examine the patterns of insecticide use by the Harris and Chambers county mosquito control districts and their potential for negatively impacting the Houston toad; to identify the areas of coincidence between Houston toad habitat and insecticide use against mosquito populations; and to optimize the protection of the Houston toad while maintaining adequate control over mosquito populations by recommending alternative control practices when and where necessary.

MATERIALS AND METHODS

Study areas: Harris and Chambers counties neighbor each other in the Coast Prairie and East Texas Timberlands Resource Areas of the Upper Gulf Coast region of southeast Texas, with Harris County being on the western border of Chambers County. Summaries of the nature of the environmental and socioeconomic conditions in Harris and Chambers counties are given by Wheeler (1976) and Crout (1976), respectively. Harris County supports the highest human populations (in excess of 2.4 million people [Hoffman 1991]) and is the most urbanized (ca. 40% of this county's 1.13 million acres is considered urban land [Wheeler 1976]) of the 2 counties. Houston is the county seat of Harris County, giving residence to approximately 1.6 million people and encompassing about 0.4 million acres of land in the county (Johnson 1995). Otherwise, the remainder of the total land area in Harris County is pasture and rangeland (25%), cropland (15%), undeveloped woodland (15%), and federal land and water areas (5%) (Wheeler 1976).

In contrast to Harris County, Chambers County is more sparsely populated (ca. 18,000 people reside in this county [Hoffman 1991]) and rural in its nature, with the farming of rice and crops rotated with rice being at the base of the economics in this particular county (Crout 1976). Of the 560,000 acres encompassed by Chambers County, 68% is land and the remainder is water, with the mouth of the Trinity River drainage system and a major portion of Trinity Bay being included inside the borders of the county (Crout 1976). Anahuac (population ca. 2,000) is the county seat of Chambers County and is located at the head of Trinity Bay. Chambers County is home to the USFWS Anahuac National Wildlife Refuge and otherwise has in excess of 120,000 acres of coastal marshland on its southeastern side that gives residence to a diversity of overwintering waterfowl as well as an even greater diversity of resident flora and fauna.

Harris and Chambers counties were chosen for the purposes of the current study because both have active mosquito control districts and both were determined to still have habitat that could support the Houston toad. The Houston toad is the endangered species chosen as the model for our study because it has sensitivity to certain of the insecticides used in the control of mosquitoes. Also, it was our desire to compare situations inherent to a highly urbanized county with those of a more rural county as it pertains to mosquito control and protection of an endangered species. Although Chambers County is not on record as currently supporting any populations of the Houston toad, Harris County to its west and Liberty County to its north have historically had populations of this toad (U.S. Fish and Wildlife Service 1984); and Chambers County does have habitat that could support the toad. It was thus decided to include Chambers County in our study rather than Liberty County, because the latter county does not have an active mosquito control program from which records of pesticide usage patterns could be obtained.

The Houston toad: The Houston toad is an endangered species historically indigenous to only a few counties along the Upper Gulf Coast of Texas (U.S. Fish and Wildlife Service 1984). Populations of this toad are found in pine or mixed deciduous forested areas, or in open grassy areas. Sandy, friable soil occurs at all known habitat locations (Brown 1971). Houston toads are weak burrowers and cannot dig in compacted soil (Bragg 1960). These toads are very secretive animals, spending most of the daylight hours buried under the sand and are usually observed only in the evenings during spawning season (U.S. Fish and Wildlife Service 1984).

Water is an extremely important limiting factor for the Houston toad. Calling and spawning are initiated by heavy rains and warming temperatures in the spring, with the earliest dates for the initiation of spawning by this species being in late February (Kennedy 1962). Spawning season is heralded by male toads emerging near breeding sites each evening just after sunset and calling for females.

Houston toads will breed in lakes, small ponds, ditches, and other deep, flooded depressions. Hillis et al. (1984) reported nonflowing pools persisting for at least 60 days to be optimum requirements for tadpole development. Tadpoles require approximately 1 month to complete their development and metamophose into adults (Kennedy 1962). Adult toads will begin estivation by the middle of June and will not be seen again until the next spring's breeding season (J. R. Dixon,[7] personal communication). When active, Houston toads are known to eat small to medium-sized beetles, flies, green lacewings, moths, and other smaller amphibians (Bragg 1960).

Although habitat destruction and climatic changes are deemed the major causes for the decline of Houston toad populations (Brown and Thomas 1982), pesticide exposure may be worsening the problem (U.S. Fish and Wildlife Service 1984, 1989). Malathion and naled, 2 organophosphate insecticide commonly used for mosquito control purposes, have both been designated by the U.S. Fish and Wildlife Service (1984) as being hazardous for Houston toads. Sanders (1970), using the tadpole stage of several amphibian species, found median lethal concentration of 0.20–0.42 ppm after 96 h for malathion. Mohanty-Hejmadi and Dutta (1981) found that chronic exposure to malathion at rates much lower than those recommended for field applications caused a prolongation of the life history of amphibians and produced smaller adults after metamorphosis. No data on naled's effects on amphibians are available; however, tests on other acetylcholinesterase-inhibiting organophosphorous compounds such as fenitrothion, fenthion, guthion, parathion, and acephate all showed harmful effects on tadpoles (Power et al. 1989), making naled suspect as well.

Mosquito control activities: The mosquito control district in Harris County has an annual operating budget of ca. $3.0 million and, as of 1990, its staff consisted of 40 full-time and 20 seasonal employees (American Mosquito Control Association 1991). This district has had a history of focusing the bulk of its mosquito control effort on the abatement of *Culex quinquefasciatus* Say populations in the interest of protecting citizens of Harris County from outbreaks of St. Louis encephalitis virus vectored by this mosquito species (Olson 1994). No aerial adulticiding is done by the district and ground adulticiding is accomplished using 20 vehicles equipped with Leco™ (Lowndes Engineering Co., Inc., Valdosta, GA) ultra-low volume (ULV) units using either malathion or the resmethrin/piperonyl butoxide (PBO) mixture marketed as Scourge™ (AgrEvo Environmental Health, Montvale, NJ). Some adulticiding may be accomplished using handheld foggers when such is needed. Harris County district does no aerial larviciding and ground larviciding is accomplished using 8 vehicles in applying formulations of the bacterial toxin, *Bacillus thuringiensis* var. *israelensis* (*B.t.i.*), with some hand applications of formulations of the insect growth regulator (IGR) methoprene also being done on occasion (Olson 1994).

The mosquito control district in Chambers County has an annual operating budget of ca. $265,000 and, as of 1990, its staff consisted of 6 full-time and 6 seasonal employees (American Mosquito Control Association 1991). The focus of this district's mosquito control activities is primarily on abating problems associated with salt-marsh and agricultural wetland floodwater mosquito species, in particular *Aedes sollicitans* (Walker), *Aedes taeniorhynchus* (Wiedemann), and *Psorophora columbiae* (Dyar and Knab). Some attention is paid to the control of *Cx. quinquefasciatus* during the late summer and early fall months and *Culex salinarius* Coquillett during the cooler months of late fall, winter, and early spring (Olson 1994). Aerial adulticiding is accomplished by Chambers County using a Twin Piper™ (New Piper Aircraft Corp., Vero Beach, FL) Aztec equipped with a Tee-jet™ (Spray Systems Co., Wheaton, IL) nozzle system so as to apply either malathion or naled at ULV rates. Ground adulticiding is accomplished using 5 vehicles equipped with either Leco or London Aire™ (London Fog, Inc., Long Lake, MN) ULV units dispensing either malathion or the resmethrin/PBO formulation, Scourge. Only a minimal amount of larviciding is done by the Chambers County district and this is accomplished using one vehicle applying formulations of either *B.t.i.* or methoprene, primarily to septic ditches containing *Cx. quinquefasciatus* larvae (Olson 1964).

Geographic information system assessment procedure: The GIS used in this study was the Geographical Analysis Support System (GRASS) designed and developed by the Environmental Division of the U.S. Army Construction Engineering Laboratory. This system was operated on a SUN™ (Sun Microsystems, Inc., Mountain View, CA) 386i microcomputer using other equipment such as a Kurta™ (Kurta Corp., Phoenix, AZ) IS/Three digitizing table and a Calcomp™ (Calcomb, Anaheim, CA) Plotmaster color plotter/printer available in the Knowledge Engineering Laboratory in the Department of Entomology at Texas A&M University, College Station.

The basic procedures followed are illustrated in Fig. 1. First, spatial databases, each consisting of

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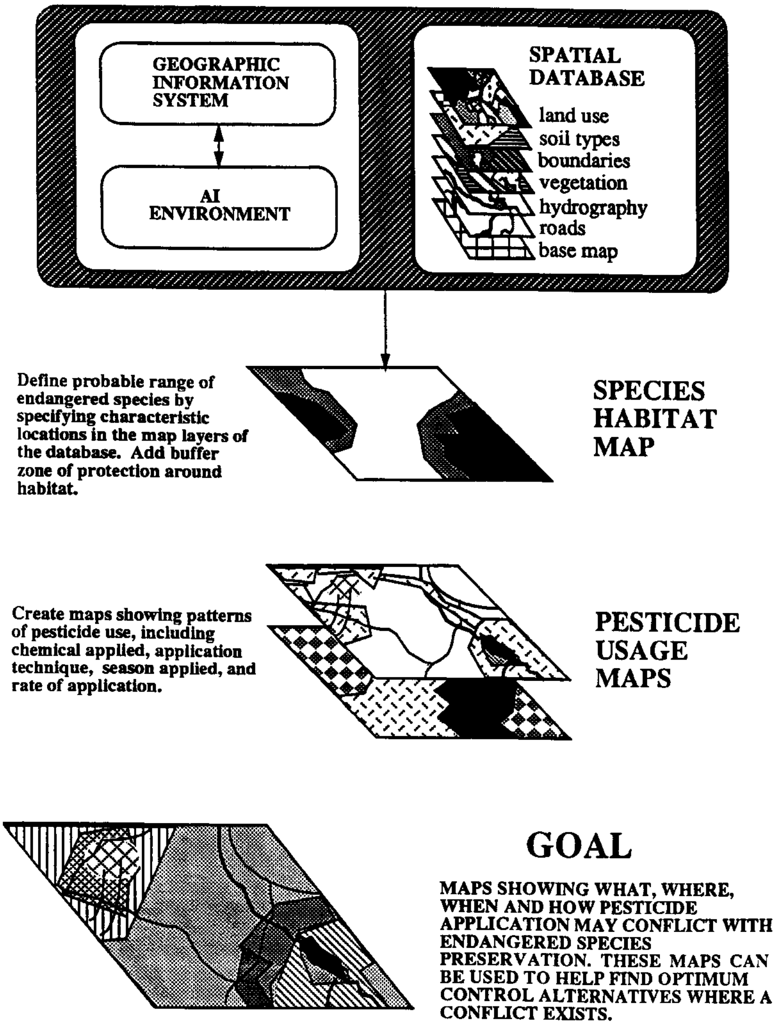

Fig. 1. Diagram illustrating the basic procedures followed in using a geographic information system (GIS) approach to determine zones of coincidence between Houston toad habitat and areas treated with insecticides for mosquitoes in Chambers and Harris counties, Texas. "AI Environment" is the term used to denote computer-supported, rule-based reasoning processes used to assess data and produce resulting maps, sometimes called "artificial intelligence" (or AI).

several themes, were assembled for Harris and Chambers counties. Data themes included land use and land cover, soil types, political boundaries, hydrography, and roads. Road and hydrography data were obtained from the U.S. Geological Survey (USGS), which distributes line map information in a digital form called a digital line graph (DLG), at a scale of 1:100,000 (U.S. Geological Survey 1985). These data files were then converted into GRASS vector files and edited as needed. Data files on roads were used mainly as points of reference. The hydrography data files were converted into cell files (grid or raster data) with 25-m resolution because GRASS can only perform analyses on cell files.

Land use, land cover, and political boundary data for Harris and Chambers counties were also ordered from the USGS, but in a 1:250,000-scale digital format that converts directly to cell files (U.S. Geological Survey 1986). The data quadrangle for the northernmost part of Harris County was unavailable for these particular themes, so the complete county was not included in the study.

General soils maps produced by the U.S. Department of Agriculture (USDA) Soil Conservation Service (SCS) for Harris County (Wheeler 1976) and Chambers County (Crout 1976) at scales of 1: 316,800 and 1:190,080, respectively, were digitized, labeled as vector files, and then converted into cell files. Because these soils maps were small and generalized, the level of detail for data digitized from these particular maps was much lower than that for the data gathered on other themes using maps from the USGS.

Once the spatial databases were assembled for Harris and Chambers counties, Houston toad species habitat maps (Fig. 1) were developed for the 2 counties. The toad's habitat was defined using the soils map, land use and land cover map, and a modified layer of the hydrography data called "waterbuffer." Based on the Houston toad's soil type preferences, all areas in each county having sandy, friable soils were identified using the general soils map theme data. Because all the soils data gathered on Harris and Chambers counties were general, suitable soil for the Houston toad was defined for the purposes of this study as any soil association where the majority of the soil series included in it were sandy and/or friable.

Categories chosen in the land use and land cover layer of theme data as habitat suitable for Houston toads included pastured land; deciduous, evergreen, and mixed forest land; and forested and nonforested wetlands. Categories of habitat preferred by the toad included in the hydrography layer of theme data were ponds, lakes, streams, wetlands, roadside ditches, and other flood-prone areas in each county. Also, using the GRASS utility *distance,* a data layer was produced that would create maps showing a 200-m zone around any body of water suitable as a site for Houston toad immature development, with this zone being the region in which adult toads would most likely occur.

The GRASS utility *Ginfer* was used to produce the species habitat maps for the Houston toad and the sets of rules describing the habitat for the toad in Chambers and Harris counties were written in a format that would be accepted by this particular program. The set of rules written for Chambers County read as follows:

```
IFMAP   pol.boundary 71
IFMAP   CC.landuse 21   41-43 61-62
IFMAP   CC.soils   3   6
IFMAP   CC.waterbuf   1   1
THENMAPHYP 1 prob.hab
```

The first statement specified that the study habitat area be limited to Chambers County. Statement 2 identified the vegetation cover types that are suitable as habitat for the Houston toad. Statement 3 identified the soil types that are suitable for the toad. Statement 4 required that all habitat areas be within 200 m of a body of water suitable for immature toad development, and Statement 5 stipulated that a new map be created within the limits of Statement 1 (i.e., for Chambers County) upon which all areas satisfying the habitat criteria specified in the program as suitable for the Houston toad would be noted.

The set of rules written for Harris County was similar and read as follows:

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IFMAP   pol.boundary 201
IFMAP   landuse 21   41-43 61-62
IFMAP   Harris.soils 2-4
IFMAP   waterbuffer 1
THENMAPHYP 1 prob.hab
```

In this set of rules, Statement 1 specified that only habitat areas within Harris County be identified. The other statements were identical to the set of rules for Chambers County, except they used the Harris County base map data.

As a final step to the species habitat mapping phase of this study, the GRASS utility *distance* was again run on the habitat data layers of both counties to produce an 800-m buffer zone of protection around each location where "ideal" habitat for Houston toads was identified in the given county. These buffer zones were meant to protect the toad habitats from pesticide drift. The distance chosen for these buffer zones in our study was somewhat arbitrary; under operational conditions, the actual distances for these zones would have to be determined on a case-by-case basis taking into account such items as type of pesticide application, formulation of pesticide being used, wind direction, and other factors affecting the potential for pesticides contaminating a given habitat location.

Pesticide records maintained by the Chambers and Harris county mosquito control districts were used as the source of data for the creation of pesticide usage maps (Fig. 1). The Chambers County district made available all of its records for the years 1984–88. During these particular years, the Chambers County district engaged in 4 different types of control tactics involving pesticides: ground adulticiding, ground larviciding, aerial adulticiding, and aerial larviciding. Ground adulticiding was most commonly conducted along streets in urban and suburban areas of the county in the early to late evening hours using truck-mounted ULV cold fogging units. The insecticides being used in this aspect of the Chambers County mosquito control program during 1984–88 were malathion, applied at 3.0 oz. AI/min at 15 mph, and naled, applied at 1.5 oz. AI/min at 15 mph. The Chambers County district kept records on this activity in vector or polygonal formats by recording the names of streets (vector format), small towns, and/or subdivisions (polygonal format) covered and insecticide used each night by its ground adulticiding crews.

In compiling, summarizing, and rasterizing the Chambers County ground adulticiding data for insertion into our computer assessment program using USGS/DLG map information (scale 1:100,000), it was found that the district included 86 different ground adulticiding treatment areas in its program during 1984–88. These data were summarized by number of treatments per month for each of the 86 areas. Insecticide usage was then classified for each area as "light" if the area was treated only 1–2 times per month; "moderate" if treated 3–5 times per month; or "heavy" if treated more than 5 times per month by ground adulticiding crews.

Ground larviciding activities in Chambers County during 1984–88 consisted of treating septic ditches in scattered areas throughout the county with diesel fuel mixed with surfactant. These locations were sprayed once a month from March through September of each year using a pump sprayer mounted on a truck.

An extensive amount of aerial adulticiding was practiced by the district in Chambers County during 1984–88, particularly in the upland areas outside cities and towns and away from the coastal marshland areas. The insecticides used by the Chambers County district in its aerial adulticiding program were malathion, applied at a rate of 1.0 oz. AI/acre during 1984–86 and resmethrin (as Scourge), applied at a rate of 1.5 oz. AI/acre during 1987–88. A total of 28 different areas in the county were treated at least once with aerially applied mosquito adulticides during 1984–88. Data reflecting the number of times each of these areas was treated with a given insecticide were placed into digitized form using daily treatment maps kept in a polygonal format (scale: 1:126,720) on county maps by the aerial spray pilot. Otherwise, the aerial adulticiding data were organized, averaged, and categorized for the purposes of our study in the same manner as was done for the ground adulticiding data.

During 1984–88, the Chambers County district occasionally aerially treated flooded rice fields with *B.t.i.* toxin formulations to control larval mosquito populations. Again, daily treatment maps kept in a polygonal format (scale: 1:126,720) by the pilot were used to digitize the larviciding location and treatment data into a form that we could use in our study.

Only 2 years of pesticide usage data (those for 1984 and 1985) were obtained from the Harris County Mosquito Control District that were in a road- and street-based format that could be rasterized for use in our study. Because of the amount of urban development present in Harris County, no aerial adulticiding was done during the years covered by these records. Also, the district practiced very little ground-level larviciding in the county, with methoprene being the agent of choice if and when any larviciding was done and septic ditches inside the city limits of Houston being the sites of these larvicidal treatments. The Harris County district did have a rather aggressive belowground, storm drain treatment program in force during the 1980s in the older sections of the city of Houston. This program was directed against both adult and larval *Cx. quinquefasciatus* populations located in these drains and involved wet fog injections of natural pyrethrum/PBO mixtures diluted in diesel fuel into the storm drains through manhole openings using thermal fogging units specially adapted for this purpose. Some aerial larviciding was being practiced by the U.S. Army Corps of Engineers in marshy areas along the Houston Ship Channel in the eastern part of Harris County. This particular larviciding activity involved the IGR methoprene aerially applied at 4.0 oz. AI/acre.

Because the various mosquito control activities described above were either so sporadic in their occurrence or deemed by us to have little or no potential effects on Houston toads by where and how these control activities were being practiced (e.g., storm drain treatments), we decided to spend the time and resources available to our study on analyzing data associated with the Harris County district's major mosquito control activity, ground adulticiding. In support of this activity, the district had divided Harris County into 265 sections, with records being kept on each time all streets in a given section were ground-treated with an adulticide using truck-mounted ULV cold fogging units. The insecticides used in these treatments were malathion, applied at 6.4 oz. AI/min at 15 mph, and resmethrin (as Scourge), applied at 5.2 oz. AI/min at 15 mph. The Harris County ground adulticiding data were placed into digitized form using the USGS/DLG road map information (scale: 1:100,000); and otherwise, these data were organized, averaged, categorized, and rasterized for each treatment section in the same manner as was done for the Chambers County ground adulticiding data.

All insecticide usage data for each of the 2 counties were further subdivided by frequency of use into seasons of the year. The months included in each season for the purposes of this study were: January–March (winter), April–June (spring), July–September (summer) and October–December (fall). Separate pesticide usage maps were then prepared for each type of insecticide application method included in the study for each county.

As the final step to the assessment process, the GRASS utility *combine* was used to identify the areas of coincidence or "conflict" between where "ideal" Houston toad habitat occurred and where applications of insecticides for mosquito control took place in Chambers and Harris counties, this being the ultimate goal of our study (Fig. 1). Maps for each type of insecticide application method for each season were compared with ideal Houston toad habitat maps for each county to identify areas of overlap. With the utility *combine,* coded statements can be written to identify coincident geographic occurrences of different categories of events in separate map layers. For example, the statement, "(NAME overlap (AND (GROUP 1 2 3 (truck2)) (GROUP 1 (probe.hab))))", will produce a map called "*overlap*" showing overlap between light, moderate, and heavy malathion use via ground application for April–June (coded truck2) and the potential habitat for the Houston toad (coded prob.hab) in Harris County.

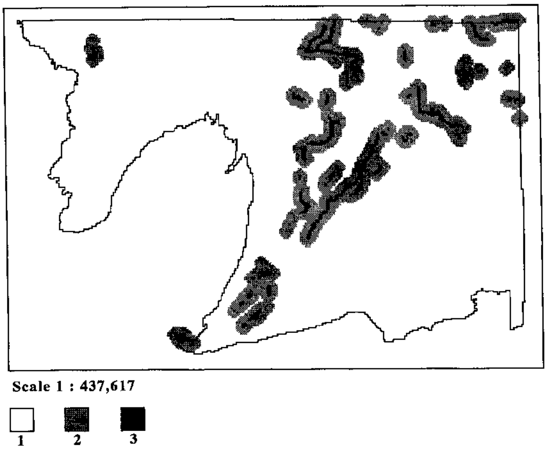


Fig. 2. Suitable habitat for the Houston toad (map shade 3) with protective buffer zone (map shade 2) in Chambers County, Texas (map shade 1), as determined by geographic information system analyses.

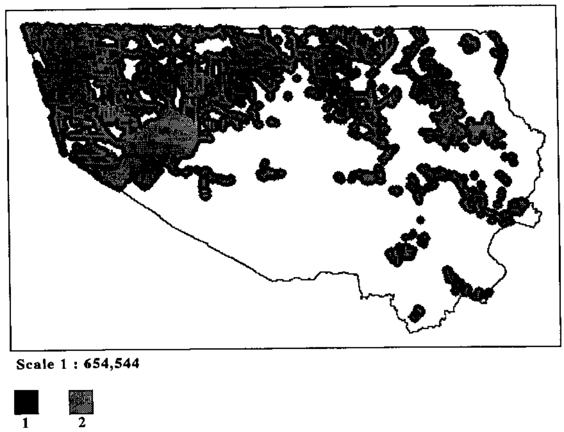


Fig. 3. Suitable habitat for the Houston toad (map shade 2) with protective buffer zone (map shade 1) in Harris County, Texas, as determined by geographic information system analyses.

RESULTS AND DISCUSSION

Houston toad habitat: Results of the *Ginfer* and *distance* utility analyses run on Chambers County toad habitat data are shown in Fig. 2 (map shade 3).[8] The 800-m buffer zones of protection around these habitats are also depicted in Fig. 2 (map shade 2). These results indicate that as many as 11,160 acres of habitat suitable for Houston toads exist in Chambers County, with 57,940 additional acres needing to be added to provide the protective buffer zone around these habitats. Thus, the toad habitat, coupled with its protective zones would amount to ca. 12% of the total acres of land (560,000) existing in Chambers County.

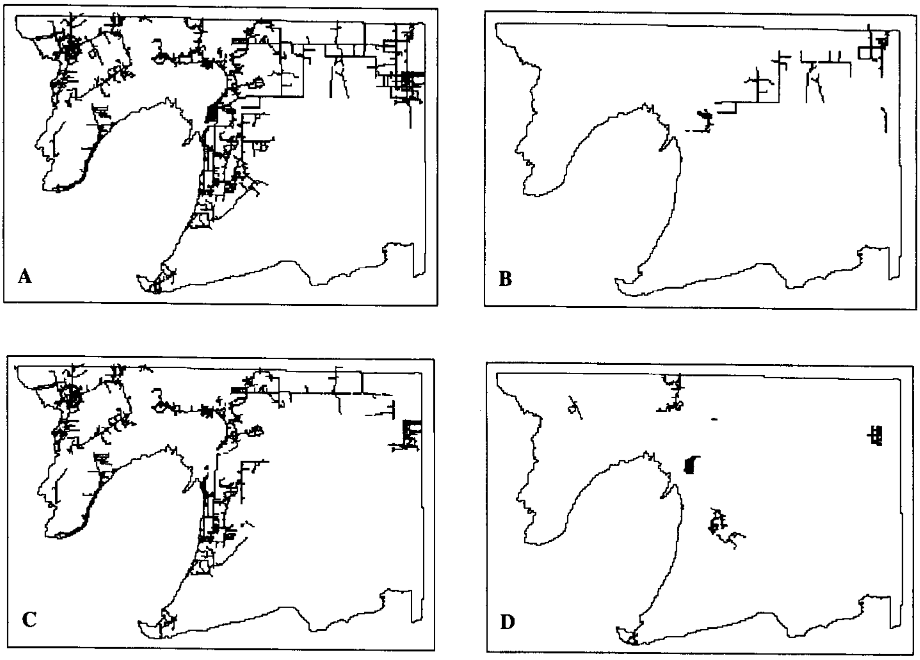
Results of the *Ginfer* and *distance* utility analyses run on the Harris County toad habitat data are shown in Fig. 3 (map shade 2). The 800-m protective buffer zones are also depicted in Fig. 3 (map shade 1). In this case, our analysis indicated that at least 149,900 acres of habitat suitable for Houston toads still exist in Harris County despite all the urbanization that has occurred in this county and keeping in mind that habitat data were not available for the northernmost region of the county. It was further estimated that an additional 308,520 acres of land would have to be included in the protective buffer zones around the toad habitat we identified as occurring in Harris County, bringing the total amount of land involved in preserving and protecting toad habitat to at least 41% of the total land area (ca. 1.3 million acres) included in Harris County.

In regard to the Harris County results, our analyses identified the sites where the Houston toad has been previously observed near Ellington Air Force Base (southeast Harris County) and in the Fairfield subdivision of Houston (northwest Harris County) (U.S. Fish and Wildlife Service 1984), giving some evidence of the accuracy of our analytical techniques. Also, our analyses indicated that the U.S. Fish and Wildlife Service (1984) may have overestimated the amount of Houston toad habitat existing in southeast Harris County on the map this agency released. In this case, the USFWS map included land in southeast Harris County whose soil contained too much clay to be suitable for the toad. In contrast, the USFWS map completely excluded the large areas of land in the northwestern part of the county identified by our analyses as suitable habitat for the Houston toad (Fig. 3).

The reason for the overestimation of toad habitat by the USFWS in southeast Harris County is probably because this agency used major highways to delineate the habitat. Our technique was more definitive in nature and excluded all the land whose soil was not suitable for the toad in this region of the county. This indicates that a habitat analysis and mapping technique such as the one we used will give a much more precise picture of what areas of land should be included and exempted from a protection program that might be implemented for an endangered species such as the Houston toad than will the method used by the USFWS. This is reinforced by our method having identified the large amount of potential habitat for the Houston toad in northwest Harris County that was not indicated as present on the USFWS map.

Pesticide usage: Examples of the types of maps produced from the pesticide usage analysis phase

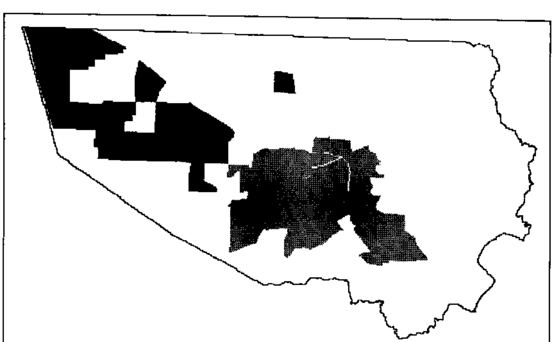
[8] In the presentation and discussion of our results, it should be noted that all the original maps produced during the course of the study were in color. However, publication of colored versions of the maps included in this paper was cost-prohibitive. Thus, the maps included herein were produced using the black and white shading features inherent to the GRASS mapping programs.



Scale 1 : 437617

Fig. 4. Regions of Chambers County, Texas, treated for mosquitoes via ground ultra-low volume adulticiding units during the January–March season. (A) All regions treated collectively; (B) regions treated 1–2 times per month; (C) regions treated 3–5 times per month; and (D) regions treated more than 5 times per month.

of our study are shown in Figs. 4 and 5. Similar maps were created by season for each type of insecticide-based mosquito control method used in Chambers and Harris counties over the years encompassed by the pesticide usage data included in this study. The Chambers County map (Fig. 4) depicts how ground adulticiding data were summarized by street location and level of treatment for a given season. On colored versions of maps of this kind, all levels of treatment could be presented on the same map using different color codes for each treatment level. The Harris County map (Fig. 5) depicts how ground adulticiding data were summarized on a land area or section basis for a given season, which was how the Harris County Mosquito Control District kept track of its insecticide usage data. Maps summarizing other types of insecticide usage data involving area-wide treatments, such as aerial adulticiding data from Chambers County, looked similar to the Harris County ground adulticiding map shown in Fig. 5 in regard to how the data were displayed on these other maps.



Scale 1 : 638,243

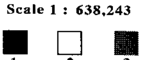


Fig. 5. Regions of Harris County, Texas, treated for mosquitoes via ground ultra-low volume adulticiding units during the July–September season. Shade 1 = regions treated 1–2 times per season; shade 2 = regions treated 3–5 times per season; shade 3 = regions treated more than 5 times per season.

Pesticide use/Houston toad coincidence analyses: In our determinations of zones of potential overlap or zones of potential conflict between the Houston toad and mosquito control activities in Chambers and Harris counties, we focused our attention primarily on mosquito insecticide usage patterns during the winter (January–March) and spring (April–June) seasons of the year. As previously noted, these seasons encompass the time of the year when the toad is on the ground surface mating, spawning, and developing and thereby, is in a position to be most exposed to the effects of any pesticides occurring in its habitat. By mid-June, the

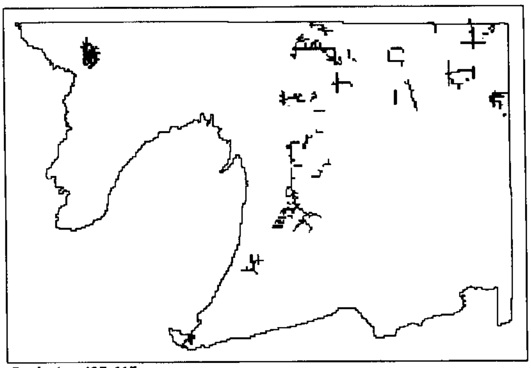


Fig. 6. Zones of overlap or coincidence (map shade 2) between Houston toad habitat and regions treated for mosquitoes via ground adulticiding units in Chambers County, Texas (map shade 1), during April–June season.

Fig. 7. Zones of overlap or coincidence (map shade 2) between Houston toad habitat and regions treated for mosquitoes via aerial applications of adulticides in Chambers County, Texas (map shade 1), at various times throughout the year.

adults burrow below the ground surface where they estivate until the following late winter or early spring (J. R. Dixon,[7] personal communication), which affords them protection against insecticides of the kind used and the ways they are applied in mosquito control programs (i.e., nonresidual pesticides applied at ULV rates).

The zones of coincidence or overlap between ideal Houston toad habitat in Chambers County and ground mosquito adulticiding activities performed by the district in this county during April–June as determined by our analyses are shown in Fig. 6. Although the Chambers County district performs ground adulticiding year-round, the April–June period of each year marks a time when this activity is most extensive and intensive due to adult *Cx. salinarius* populations reaching their peak period of spring activity in the county (Janousek and Olson 1998) and the emergence of a variety of floodwater mosquito species activated in the coastal salt marshes and upland agricultural areas by natural flooding and the purposeful flooding of rice fields. Thus, it would be during this time of the year and in the zones depicted on the map in Fig. 6 that the greatest amount of conflict between Houston toad protection and ground adulticiding for mosquitoes would occur.

To resolve this problem, it would be our recommendation that the Chambers County district refrain from using organophosphorus adulticides in the zones of Houston toad coincidence during the first 6 months of the year, because it is these particular chemicals (e.g., malathion and naled) that have the greatest potential of causing harm to exposed toads (U.S. Fish and Wildlife Service 1984). If ground adulticiding is necessary in the zones of toad coincidence during these months, perhaps adulticidal formulations having resmethrin as their active ingredient could be used, because this chemical, according to its label, is not harmful to amphibians in the manner it is applied for control of adult mosquitoes. The district could then return to the use of malathion and other organophosphorous adulticides in these zones during the other 6 months of the year when the toads are below ground surface estivating.

The zones of coincidence between the Houston toad and the aerial mosquito adulticiding program in Chambers County as determined by our analyses are shown in Fig. 7. The amount of area included in the Chambers County district's aerial adulticiding program is quite extensive and correspondingly, a greater amount of toad habitat in the county stands to be impacted by this approach to adult mosquito control than is the case when ground adulticiding tactics are used. Our recommendation in this case would be the same as was made for the district's ground adulticiding program; that is, in the first 6 months of the year, avoid treating the zones of coincidence when possible and, when such treatments are necessary, use a safe alternative to organophosphorous adulticides. Also, because drift of aerially applied adulticides may exceed the 800-m buffer zone we placed around the toad habitats in our study, the dimensions of these buffer zones may have to be altered to suit prevailing wind conditions so as to ensure no harmful pesticides drift into the toad's habitat during critical times of the year.

The Harris County Mosquito Control District does not usually adulticide for mosquitoes during the winter (i.e., from January to March). This leaves only the season of April–June open as a time of potential exposure of the toad to mosquito control chemicals in Harris County. During April–June, pesticide usage data indicate that the entire Harris

County is treated with ground-applied adulticides. Thus, all the toad habitat shown in Fig. 3 can be affected during this time of the year. The recommendation to the Harris County district as to how to avoid conflict between the survival of the toad and the maintenance of an effective mosquito control program using ground-applied adulticides would be the same as was recommended to the Chambers County district for both its ground and aerial adulticide programs.

The other types of mosquito insecticide application methods used by the Chambers and Harris county mosquito control districts were analyzed for zones of coincidence in the same manner as were the ones just described. None of these other types of insecticide application methods were deemed to have any possible impact on the Houston toad by nature of what insecticide was being used, where it was being used, and/or when it was being used.

CONCLUSIONS

The results of this study demonstrate that a GIS is a potentially effective tool for implementing the USFWS ESPP. A GIS allows for knowledge from different types of experts, such as wildlife biologists, geographers, and entomologists, to be written into code and then used to highlight problems requiring judgement. A GIS allows the user to quickly and more precisely visualize where a problem may occur and identify acceptable solutions. Once databases, such as were developed for Harris and Chambers counties in this study, are completed, they are relatively permanent and can be used to address other problems relating to the same issues for which the databases were originally developed. For instance, if a new endangered species is identified in Harris County or Chambers County, its probable habitat can be identified and located using the habitat information already stored in the GIS databases. Similarly, the overlap and potential effects of mosquito control on this new endangered species could be assessed in much the same manner as was done for the Houston toad using the pesticide usage stored in the database. Above all, GIS can be used to pinpoint the exact locations where and times when conflicts between a species struggling to survive and human-caused impacts on this species' survival coincide. This, then, allows for a more precise and efficient means to either avoid such conflicts or to make adjustments to human activities that will eliminate the problem that is causing the conflict.

Costs associated with making GIS evaluations of the kind described herein can be held to a minimum by making use of inexpensive software and currently available datasets, as was done in our study. However, one caution in this regard is that the degree of accuracy of the information included in the software and datasets (as affected by such things as map scales) will have influence on the accuracy of the resulting GIS-generated maps, and this must be taken into account when using this information to draw conclusions and make decisions.

ACKNOWLEDGMENTS

This paper is dedicated to the memory of Jacob White, former Director of the Chambers County Mosquito Control District. Appreciation is extended to both the Chambers County and Harris County Mosquito Control Districts and their respective personnel for the assistance and support they gave to us in securing the insecticide usage data that were used in this study.

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