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Using GIS and historical records to reconstruct residential exposure to large-scale pesticide application

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Investigation of pesticide impacts on human health depends on good measures of exposure. Historical exposure data are needed to study health outcomes, such as cancer, that involve long latency periods, and other outcomes that are a function of the timing of exposure. Environmental or biological samples collected at the time of epidemiologic study may not represent historical exposure levels. To study the relationship between residential exposure to pesticides and breast cancer on Cape Cod, Massachusetts, historical records of pesticide use were integrated into a geographic information system (GIS) to estimate exposures from large-scale pesticide applications between 1948 and 1995. Information on pesticide use for gypsy moth and other tree/vegetative pest control, cranberry bog cultivation, other agriculture, mosquito control, recreational turf management, and rights-of-way maintenance is included in the database. Residents living within or near pesticide use areas may be exposed through inhalation due to drift and volatilization and through dermal contact and ingestion at the time of application or in later years from pesticides that deposit on soil, accumulate in crops, or migrate to groundwater. Procedures were developed to use the GIS to estimate the relative intensity of past exposures at each study subject's Cape Cod addresses over the past 40 years, taking into account local meteorological data, distance and direction from a residence to a pesticide use source area, size of the source area, application by ground-based or aerial methods, and persistent or nonpersistent character of the pesticide applied. The resulting individual-level estimates of relative exposure intensity can be used in conjunction with interview data to obtain more complete exposure assessment in an epidemiologic study. While the database can improve environmental epidemiological studies involving pesticides, it simultaneously illustrates important data gaps that cannot be filled. Studies such as this one have the potential to identify preventable causes of disease and guide public policies.
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Introduction

Large-scale application of pesticides on agricultural and recreational land, forests, and wetlands for purposes of crop protection and control of insects (such as gypsy moths and mosquitoes) results in exposure of residential populations bordering or within the application area. Exposures may be from dermal contact, inhalation, or ingestion *via* food, drinking water, or contact with soil or dust. For persistent pesticides, such as organochlorines, exposures continue years after the chemicals are applied. Understanding the long-term health effects of residential exposures to large-scale pesticide application is important because it may identify preventable causes of disease. It also may guide programs to reduce exposure to banned and current use chemicals and public policies regarding registration of pesticides for particular uses, notification of neighbors about application, and land use planning.

Studies of possible long-term health effects from residential exposure to large-scale pesticide use pose challenging problems for exposure assessment, however. Residents cannot self-report these exposures because they are unlikely to know what pesticides have been used in their vicinity. Environmental and biological exposure measurements are valuable, but they are expensive and may not provide adequate assessment of exposure during the etiologic period for disease. Faced with these limitations,

1. Abbreviations: GIS, geographic information systems; CCMCP, Cape Cod Mosquito Control Project; MA-DEM, Massachusetts Department of Environmental Management; USGS, United States Geological Survey; ISCST3, Industrial Source Complex Short-Term air model; APHIS, US Department of Agriculture Animal and Plant Health Inspection Service; USDA, US Department of Agriculture; US EPA, US Environmental Protection Agency; MA DFA, Massachusetts Department of Food and Agriculture; MA DNR, Massachusetts Department of Natural Resources; ORETF, Outdoor Residential Exposure Task Force; NCFAP, National Center for Food and Agricultural Policy.

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epidemiologists often have relied on simple proxies, such as distance from agricultural land. For example, on Cape Cod, Massachusetts, where the present study is based, previous research showed an association between brain cancer risk and distance and direction of subjects' homes from cranberry bogs (Aschengrau et al., 1996). For Long Island, O'Leary et al. (2000) reported an association between breast cancer risk and residence within 1 mile of waste sites where organochlorine pesticides were disposed.

New geographic information system (GIS) technology makes it possible to improve on distance-based methods to develop a more detailed historical reconstruction of exposures. This paper reports on the application of GIS technology in conjunction with historical pesticide use records to reconstruct estimated exposures from the 1950s to the 1990s at individual addresses on Cape Cod. This work is part of the exposure assessment for the case–control epidemiologic study of 2100 women in the Cape Cod Breast Cancer and Environment Study (Cape Cod Study). The goals of this paper are (1) to describe methods for developing a GIS for exposure assessment, so that similar methods may be applied and improved upon in other studies and (2) to provide descriptive information about historical pesticide use on Cape Cod that may be compared with other geographic areas to assess whether regional differences in pesticide use may plausibly be related to differences in disease rates.

The possible role of pesticides in breast cancer risk is of concern because incidence in the US has risen more than twofold since the modern pesticide era began with the introduction of DDT in the late 1940s, and many pesticides or their breakdown products mimic estrogen, which is known to increase breast cancer risk, or otherwise disrupt hormones (Davis et al., 1993; Soto et al., 1995; Rudel et al., 2001). Previous studies of serum or adipose levels of DDT, dieldrin, and some other organochlorine compounds for the most part show no association between these pesticides and breast cancer risk (reviewed in Snedeker, 2001); however, exposure assessment in these studies reflects cumulative lifetime exposure minus excretion assessed at one point in time, thus limiting confidence that the studies measure exposures most relevant to breast cancer etiology. For example, Snedeker (2001) notes that studies that rely on recent biological measures of exposure may not be measuring primarily exposure directly to DDT (e.g., when it was sprayed as a pesticide), but rather exposure to the less estrogenic breakdown product, p,p'-DDE, ingested in food.

On Cape Cod, breast cancer incidence has been elevated in comparison with other areas of Massachusetts, even after statistically controlling for a long list of established and hypothesized risk factors for breast cancer, including family and reproductive history, physical exercise, alcohol, tobacco, and certain aspects of diet (Silent Spring Institute, 1997). More generally, a large twin study has shown that only 27% of breast cancer risk is likely due to inherited genetic variations (Lichtenstein et al., 2000), and most breast cancer risks and geographic variations in breast cancer risk remain unexplained by previous research (Madigan et al., 1995; Sturgeon et al., 1995). Thus, investigation of other possible risk factors, including environmental pollutants, is important, and Cape Cod may offer a unique opportunity to identify environmental factors. In light of previous research, the Cape Cod Study is investigating exposures to pesticides and to endocrine disruptors and animal mammary carcinogens from common products and environmental pollutants, including alkylphenols and phthalates from detergents and plastics (Brody et al., 1998; Rudel et al., 1998; Rudel et al., 2001). Exposure assessment includes interview responses for home product use, including home use of pesticides, and GIS for exposures from large-scale pesticide applications and other nonpesticide exposures.

GIS in Exposure Assessment

Geographically based historical data have long been an important resource in epidemiologic studies because they provide information about environmental exposures that study participants cannot report themselves, they are not subject to recall bias, and they provide information relevant to the etiologic period for diseases with long latency or a critical exposure period. GIS technology provides added capabilities to combine multiple data sources in complex ways that better estimate exposures.

A GIS is a computer mapping database that associates data with a point, line, or polygon on a map (Betts, 1997). Data are organized in "coverages" that include geographic information with an associated table of attributes. In health studies, spatial coordinates are linked with temporal and quantitative information representing the dates and levels of exposure (Vine et al., 1997). Coverages may be grouped together in one map as if they were transparencies layered on an overhead projector, and new maps may be created by manipulating multiple coverages and using algorithms to model environmental processes.

In recent years, researchers have begun to explore these capabilities in novel applications of GIS for epidemiologic studies of historical residential exposure to large-scale pesticide application. In a feasibility study for exposure assessment in a case–control epidemiologic study of non-Hodgkin's lymphoma, Ward et al. (2000) used 1984 satellite imagery and historical records to reconstruct crop maps. They calculated the number of acres of specific crops and total crops within a 500-m buffer around each subject's residence at the time of interview, the average distance from the residence to the centroid of crop fields within the buffer, and the crop-specific probability of pesticide use. They anticipate incorporating in future work the pesticide application rate and wind direction to predict the area affected by primary drift at the time of pesticide application. Using similar methods, Xiang et al. (2000), in a study of birth weight and crop production, generated circular buffers of 300 and 500 m around each maternal residence and calculated percentages of area covered by all crops and by individual species. Total crop area (p=0.058), sugar beets (p=0.05), and corn (p=0.1) were associated with low birth weight, with other factors controlled. In another recent study, Bell et al. (2001), using daily pesticide application information from the California Pesticide Use Report database, found elevated risk of fetal death due to congenital anomalies when pesticides were applied during the third to eighth week of pregnancy in the square mile of the mother's residence or in one of the adjacent square miles. Previous research by Simcox et al. (1995) provides evidence of higher concentrations of pesticides in house dust and soil samples near areas of current agricultural pesticide use, lending support to the use of distance-based GIS exposure measures, such as these.

The present study extends these techniques by considering more diverse pesticide uses over an extended time period and incorporating air modeling of drift from aerial application. Methods include standard techniques to calculate distances and create buffers to differentiate "exposed" and "unexposed" addresses and new GIS tools developed in this study. The study also examines limitations due to missing data and other sources of uncertainty in underlying coverages.

Table 1. Data sources for historical pesticide use on Cape Cod.

Federal
Cape Cod National Seashore
Massachusetts Military Reservation, Installation Restoration Program
US Department of Agriculture, Animal and Plant Health Inspection Service, Otis Methods Development Center
US Environmental Protection Agency
US Forest Service
University of Massachusetts Cranberry Experiment Station
University of Massachusetts Extension, Agroecology Program, Integrated Pest Management (IPM) Team
State
Massachusetts Department of Environmental Management, Bureau of Shade Tree Management and Division of Fisheries and Wildlife
Massachusetts Department of Food and Agriculture, Pesticide Bureau
Massachusetts Department of Environmental Protection
Regional, local
Towns of Barnstable, Falmouth, Mashpee, Truro, Wellfleet
Cape Cod Commission
Cape Cod Mosquito Control Project
Cape Cod Newspaper Microfiche Archives
Plymouth County Mosquito Control Project
Associations
Cape Cod Cranberry Grower's Association
Cape Cod Turf Managers Association
Cranberry Growers' Services
Golf Course Superintendents at 25 Cape Cod Golf Courses
New England Golf Course Superintendents Association

Methods

Historical Pesticide Use Data

Historical data were sought for a variety of pesticide uses: large-scale pest control for gypsy moth, brown-tail moth, and other pests that feed on trees, shrubs, and other vegetation (referred to hereafter as tree pests); control of mosquitoes and ticks; agriculture, particularly cranberry cultivation; recreational land and turf management, including campgrounds, lakes, and golf courses; applications to clear vegetation on utility and railroad rights-of-way; and residential indoor and lawn care uses. Historical information was gathered in individual interviews and focus groups with Cape Cod residents, land managers, pesticide applicators, professional associations, and public officials. These methods yielded information about target pests, governmental jurisdictions for pest control, and anecdotal accounts that led us to written records. Records were identified from local, state, and federal agencies. Data sources are summarized in Table 1.

Records were reviewed with the goal of identifying the year of application, target pest, location treated, pesticide active ingredient and formulation, application method, and meteorological conditions. For tree pest control, state and federal records were reviewed. For cranberry cultivation, historical records of approved and recommended practices, bog locations, and years of cultivation were obtained from trade organizations, academic institutions, and government agencies. For turf management on golf courses, years of operation were confirmed by telephoning individual golf courses, and locations and chemical use practices were identified through government agencies, trade associations, and individual managers. Massachusetts Department of Environmental Management (MA-DEM) pest surveillance data were reviewed to determine the years when infestations of gypsy moth on the Cape were heaviest (Massachusetts Department of Environmental Management, 1991) and local newspaper files were searched for legal notices and news reports of pesticide applications. This information provided a check for the completeness and accuracy of the pesticide use records that were identified and focused subsequent searches to fill possible data gaps on years and locations where infestations were identified.

Publicly available data for three principle types of pesticide use—large-scale tree pest control, cranberry cultivation, and golf course turf management—best met the data collection goals, and these pesticide uses became the focus of further investigation reported here. For pesticides used on agricultural land other than cranberry bogs, recreational land other than golf courses, mosquito control, and rights-of-way, historical information was inadequate to improve on historical land use as a proxy for exposure. For tick control, historical use practices were identified, but locations at playgrounds, parks, beaches, roadsides, and other public spaces could not be systematically identified, and these uses were excluded from further study. For home and garden use, historical records of sales volumes or other indicators of use were not identified, and these uses also were excluded from the GIS, although they were assessed in interviews that will be linked with GIS-based exposure data in the case–control study.

GIS Coverages

Data were incorporated into the GIS using ARC/INFO and ArcView software operating on a UNIX-based Sun ultra 10 workstation. Digitizing was done on a Calcomp Drawing Board III. The workstation is networked with a WindowsNT server that can link the GIS data to data in other applications including Microsoft Access databases. Data from the GIS can also be exported for use with other software packages to conduct statistical analyses.

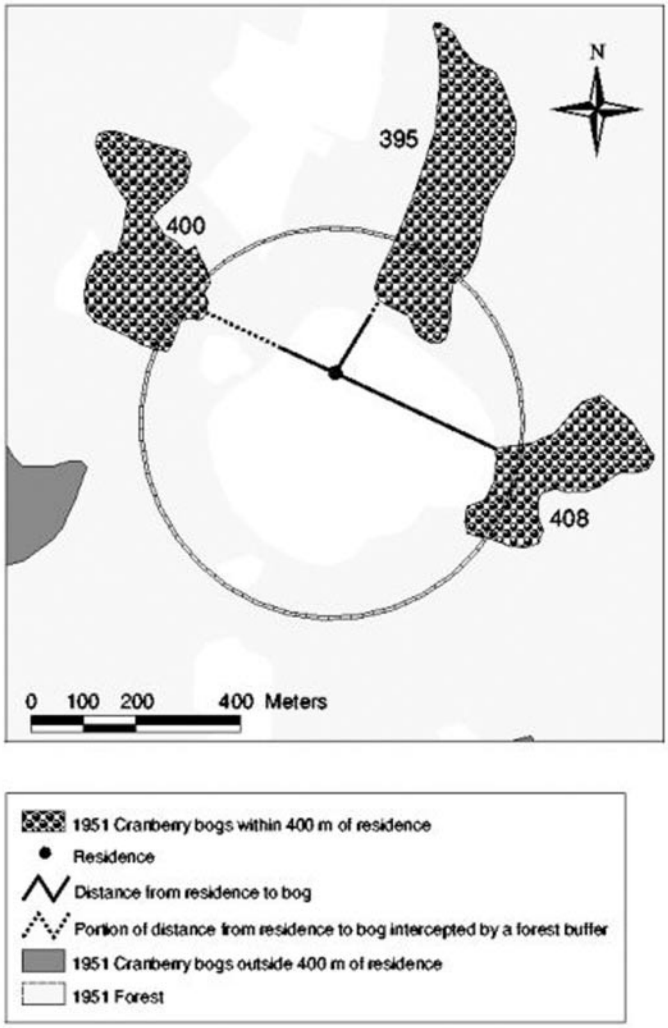
In addition to pesticide use information digitized for this study, the GIS exposure assessment relies on several existing coverages. Locations of cranberry bogs, agricultural land, and golf courses were developed from the MacConnell series of land use coverages, which are based on aerial photographs by the Resource Mapping Project at the University of Massachusetts-Amherst (MacConnell, 1975; MacConnell et al., 1984). Land use coverages for Cape Cod provide data for 4 years: 1951, 1971, 1984, and 1990. They delineate 26 types of land use, including agricultural land, golf courses, and residential areas of varying population density. Resolution is 3 acres for 1951 and 1 acre for the later years. Cranberry bogs, which represent the largest crop, can be specifically identified, but other crops cannot be differentiated. Agricultural lands other than cranberry bogs typically were truck farms growing a variety of vegetables and fruits.

Additional coverages were obtained from MassGIS, a state office within the Massachusetts Executive Office of Environmental Affairs. The MassGIS hydrography coverage, which is based on United States Geological Survey (USGS) quadrangle maps, and wetland coverages, based on orthophotos from the 1990s, were used to identify smaller cranberry bogs. Wetlands locations were identified from the hydrography coverage for fresh and salt wetlands, excluding cranberry bogs. Locations of railroad rights-of-way were identified from MassGIS transportation data, the Cape Cod Commission bike path coverage, and historical paper maps. The locations of power line rights-of-way were identified from paper maps and incorporated in the GIS using parcel and street information. GIS coverages identifying areas of insect infestation were obtained from MassGIS. Coverages showing property boundaries, referred to as parcels, were obtained from the Cape Cod Commission and the Town of Barnstable. Parcel data were incorporated into the GIS to link environmental data coverages with the Cape Cod addresses where individual study subjects resided over the past 40 years. Study subjects' addresses were obtained in interviews and geocoded to the centers of the parcels. Analysis of a representative set of 4000 residential addresses showed that the average parcel size is 0.7 acres (SD=1.44 acres) and the largest residential parcel in the set is 33.3 acres. The test addresses are described in further detail later in this paper, and additional details about GIS coverages and technologies are found in reports of the Cape Cod Study (Silent Spring Institute, 1997, 2000b).

Estimating Exposures at Residential Addresses

A computer program, referred to as the Spatial Proximity Tool, was developed to link subjects' addresses with environmental data, taking into account multiple factors to estimate the relative intensity and the duration of historical exposures to individual women. It calculates distance, direction, and other geographically based information from multiple coverages while maintaining links to the database containing attributes of the exposure sources, such as the type of pesticide applied. Output includes the distance from a subject's residence to the perimeter of the nearest pesticide use area (or other feature) or to all such areas within a specified distance and the direction of the vector from the exposure source to the subject's residence. The tool can provide the total area of the source polygon or the area of the source polygon that lies within a specified distance. It can also identify polygons that lie between the source and the subject (e.g., a forest buffer that may block pesticide drift) and provide the length of the segment of the vector that intersects these polygons. In addition, the tool can identify point and line features, such as powerline and railroad rights-of-way, and provide distances from these sources to residences. These outputs form the basis for defining a residence as "exposed" or "unexposed" during each year and for calculating relative exposure intensities that quantitatively characterize exposure levels at each residence with respect to others.

The Spatial Proximity Tool was developed using Avenue, the ArcView programming language. It is designed to be an ArcView extension that can be accessed *via* an icon in the toolbar. A series of dialogue boxes walks the user through the process of selecting the parameters needed to run the program. One output of the tool, as shown in Figure 1, is a table that includes a row for each combination of study subject, residential address, and exposure source parameters. Each combination may be characterized as "exposed" or "unexposed" and a relative exposure score may be calculated for each exposed



Residence ID	Bog ID	Period	Distance (m)	Azimuth	Direction	Forest Buffer	Buffer Depth (m)	Bog Area (acres)
001	408	1	367	295	NW	0	0	13.360
001	400	1	293	115	SE	1	170	16.856
001	395	1	174	212	SW	1	40	21.914

Figure 1. Mapped and tabulated output from the Spatial Proximity Tool. The table shows distances from an exposed residence to three cranberry bogs in the 1951 land use coverage and the direction, presence of intervening forest (0 indicates no forest buffer), depth of intervening forest, and areas (in acres) of the bogs.

combination. Defining a distance beyond which a residence is classified as unexposed is a practical approach to limiting the number of residences for which relative exposure must be calculated without loss of meaningful information.

The distances used to differentiate "exposed" and "unexposed" were based on a review of previous field study data on aerial applications (Clark et al., 1993; Bird, 1995; Bird et al., 1996; Bird, 1997; Longley et al., 1997) and were supported by transport modeling in this study (Drivas, 2000). For aerial application of pesticides (tree pest spraying and cranberry bogs), a residence was classified as "exposed" if it was located within 400 m of a spray area. For ground application (golf courses and rights-of-way), a residence was classified as "exposed" if it was within 40 m of a source. For pesticide uses that historically included both aerial and ground applications (mosquito control and agriculture other than cranberry bogs), the 400-m exposure cutoff was used in order to better differentiate a "low" exposure group. Because forested areas between a residence and a source may function as buffers limiting pesticide drift (Rathburn and Dukes, 1989; Davis et al., 1994; Longley et al., 1997), the tool provides the option of classifying a residence as "unexposed" if land use maps show that forested land separated the residence from the source.

For persistent pesticides, a residence was classified as exposed both during and after the year of application. For nonpersistent pesticides, a residence was classified as exposed only during the application year. For tree pest applications, recorded application years were used. For other applications (e.g., agriculture), yearly application was assumed during years in which the source was present and historical records indicated that pesticide use was a typical practice.

Relative exposure intensity was calculated for exposed residences. For pesticide applications by aerial spraying for tree pests or on cranberry bogs, transport modeling was conducted to develop better estimates of relative exposure. This modeling also informed calculations for other pesticide uses.

Transport Modeling of Relative Deposition Intensity from Aerial Application for Tree Pests and Cranberry Bogs The Spatial Proximity Tool was refined to incorporate results of transport modeling. The objective was to develop mathematical algorithms to estimate relative exposure based on distance and direction from a sprayed area, the size of the sprayed area, and local meteorological data. The Spray Drift Task Force AgDRIFT model (Teske et al., 1997), developed by a consortium of private companies, was used to estimate the droplet size distribution during spraying, and the US Environmental Protection Agency (US EPA) Industrial Source Complex Short-Term (ISCST3) air model (US Environmental Protection Agency, 1995; Kumar et al., 1999) was used to predict air concentrations and surface deposition of pesticides in the vicinity of the sprayed area. Application of the model does not depend on the specific pesticide active ingredient applied.

Wind roses from the National Climatic Data Center for Falmouth, Hyannis, Chatham, and Provincetown were similar to one another and consistent from year to year; but data were most complete for Falmouth, so Falmouth 1999 data were inputted as representative of the Cape. Based on reports of aerial pesticide application practices on the Cape, modeling calculations used meteorological data from April through June, 6–10 a.m., when wind speed was less than 15 miles/h and there was no precipitation. Wind rose data also were reviewed for July through September, when some spraying took place, and the pattern was similar. It is notable that the average annual wind rose for the region shows winds predominantly from the southwest, while climate data restricted to the times typical of pesticide application show winds were predominantly from the northeast and secondarily from the southwest. Mixing heights (temperature inversion heights) were obtained from upper air data for Chatham (Drivas, 2000).

Air concentration and deposition of pesticides predicted by the transport model were plotted against the distance from the source and a power law best fit was used to derive the following algorithm for estimating relative exposure (RE) for residences near aerial applications:

$$\mathrm{RE} = bX^{[c\ln A+d]}$$

where X=distance from edge of sprayed area; A=size of sprayed area; b, c, d=direction-dependent constants.

Direction-dependent constants c and d were derived from the power law best fit of model output for each of four orientations from a source to a residence (NE, SE, NW, SW) to account for wind direction. The direction-dependent constant b was incorporated to normalize relative intensities in each of the other three directions to those computed for the direction (NE) in which maximum impact was observed in this study. These constants differ between the cranberry bog and tree pest spraying models because aircraft spray height, which affects drift distance, is higher above trees than above bogs.

Constants were obtained from modeling both deposition and air concentrations at various distances from the source. Patterns of exposure intensity with distance from the source were similar for both, so equations associated with

Table 2. Relative exposure (RE) to surface deposition.

Source	Algorithm	Quadrant	b	c	d
Cranberry bogs	$\mathrm{RE} = b(X/10)^{[c\ln A+d]}$	Northeast	1.00	0.25	−2.39
		Southeast	0.53	0.21	−2.36
		Southwest	0.79	0.25	−2.63
		Northwest	0.17	0.28	−2.87
Areas treated for tree pests	$\mathrm{RE} = b(Z/25)^{[c\ln A+d]}$	Northeast	1.00	0.12	−1.87
		Southeast	0.55	0.13	−2.13
		Southwest	0.63	0.18	−2.33
		Northwest	0.25	0.20	−2.55

X=distance from bog area boundary (10–400 m); A=area of source (acres); Z=distance from forest area boundary (25–400 m).

deposition modeling were selected. Deposition falls off more rapidly than air concentration, so it is a better means of identifying the most highly exposed subjects. The relative deposition algorithm is valid for a specific range of distances: 10–400 m for cranberry bogs and 25–400 m for tree pest spraying. Constants are shown in Table 2. Figure 2 is a visual representation, drawn with a contouring program, of direction-dependent deposition predicted for a circular 5-acre bog, showing the effect of meteorological conditions on drift. Note, however, that relative exposures are calculated from the location of each residence, not from the location of the bog.

For residences inside a pesticide source area, modeling results show that deposition is approximately constant at about 16 (for bogs) to 17 (for tree pest spraying) times the maximum value predicted at the lower distance limit for which the relative deposition algorithm is valid (25 m from the boundary for tree pest spraying and 10 m from cranberry bogs).[3]

To further evaluate the model, we tested its sensitivity to assumptions about the droplet size distribution, which is a critical input to the ISCST3 model. Droplet size is primarily a function of physical characteristics of the aircraft and spray nozzle, and these characteristics are uncertain for the historical uses studied here. For the droplet size distributions we tested (mass mean diameters 120–350 μm), model output differed by a factor of 2 or less from the distribution we used (mass mean diameter 240 μm). (Drivas, 2001)

Transport modeling for tree pest and cranberry bog spraying also provides guidance in evaluating which parameters are likely to be the best indicators of relative deposition for pesticides used for a variety of purposes that were not modeled (e.g., mosquito control). These uses were not modeled because application methods were more varied than the aerial application methods used for tree pests and cranberry bogs. Modeling showed that close to a source, deposition depends on distance from the source and is nearly independent of the area of the source, since a close location can be affected by only a small portion of the total area. Based on this observation, relative exposure intensity for residences exposed to pesticides used for agriculture (other than cranberry bogs), mosquito control, golf courses, and rights-of-way was calculated as the inverse of the distance squared from the residence to the boundary of the source.

Additional details of the modeling are found in Drivas (2000, 2001). The relative exposure intensities calculated by the model are not regarded as exposure concentrations, but as proxies for exposures through all routes that are approximately proportional to actual exposures, so that they are useful in ranking study subjects' relative exposure. Relative exposure intensities were assumed to be additive for residences exposed to multiple sources within a single pesticide use category, e.g., multiple cranberry bogs.

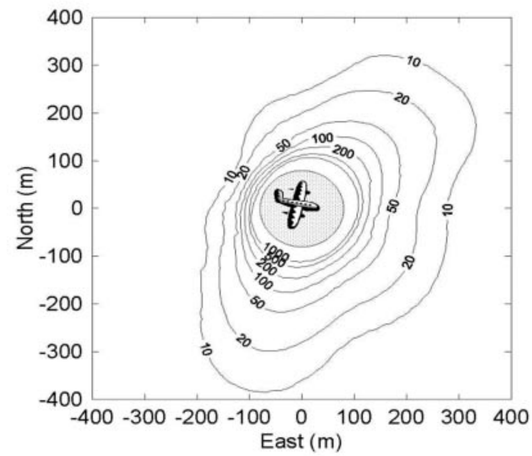


Figure 2. Contours of total deposition (g/m^2) for aerial pesticide application on a 5-acre bog in April–June, 6–10 a.m. Contours were generated using ISCT3 model output, which is the basis for algorithms estimating relative deposition at a residence.

Evaluation of Exposure Variables Using Test Addresses

The Spatial Proximity Tool was used to analyze exposures at approximately 4000 test addresses. Test addresses were selected using land use, US Census, and parcel data to create a set of addresses that were distributed throughout the Cape in roughly the same density as the age-stratified distribution of subjects in the case–control study. Calculations using this address set tested the computational efficiency of the Spatial Proximity Tool and provided an opportunity to evaluate the likely distribution of the exposure variables in the case–control study, independent of any knowledge of the characteristics of breast cancer cases. The exposure assessment in the case–control study will calculate exposures separately for each year and aggregate them for each study subject; however, this preliminary test of the Spatial Proximity Tool calculated exposures for only 4 single years: 1951, 1971, 1984, and 1990 — the years represented in the MacConnell land use coverages. Exposures to Cape-wide spraying in 1949–1950 and 1955 (see Results) were excluded because a primary goal of the test address analysis was to evaluate variability in the exposure variables. In the case–control study, calculations will assume that land use changes occurred in the middle years between the dates of the land use coverages. The Cape experienced substantial residential development and loss of forest and agriculture during the study years (Silent Spring Institute, 2000a).

[3] For residences located between the boundary of a source and the 25- and 10-m limits for the transport modeling algorithm, relative exposure was assumed to decrease linearly as distance from the source increases.

Results

Gypsy Moth and Other Vegetative Pests

Large-scale pesticide application for control of gypsy moth and other tree pests was one of the primary historical uses of pesticides on Cape Cod, affecting nearly every acre of land. Extensive residential development on the Cape since the 1970s resulted in new opportunities for exposure as homes were built in areas previously treated with persistent pesticides.

Data for every spray event identified in this study for large-scale tree pest control are accessible in the *Cape Cod Breast Cancer and Environment Atlas* at www.SilentSpring.org. Information, where available, includes the year, target pest, location, active ingredient, and application method. Maps of tree pest applications for which the location is recorded in sufficient detail also are shown in the online atlas. Table 3 is an excerpt of the recorded spray events data, showing spray events for the 1960s as an example of the data identified. These years show the transition from DDT and dieldrin to Sevin and Gardona.

Beginning in the early 1900s, federal, state, and local agencies conducted tree pest control programs using mechanical methods and an evolving list of chemical agents beginning with creosote and lead arsenate. Chemical agents shifted to DDT, dieldrin, and other persistent organochlorines from 1948 to 1965. Gardona, carbaryl (Sevin), malathion, methoxychlor, daconil, and benlate were used during the late 1960s through the end of the study period in the early 1990s. Chemical treatments are typically during the larval stage (May and June). Biological agents, such as *Bacillus thuringiensis*, have replaced some chemical pesticide use during this period (Massachusetts Department of Natural Resources, 1974), but these are not included in the database because the biological active ingredient is not a focus of this study.

Records show substantial use of organochlorine pesticides, particularly for gypsy moths. DDT was first used for gypsy moth control on the Cape in a 1948 pilot program, and in 1949–1950, federal and state officials attempted to eradicate the gypsy moth by spraying nearly all of Cape Cod with DDT (Massachusetts Department of Environmental Conservation, 1949). Nearly all of the Cape was treated with DDT again in 1955, and portions were treated in other years as well. For the period 1961–1965, Cape Study data show pesticide use areas in the upper and lower Cape, but none in the mid Cape, and the MassGIS insect infestation coverages for the same period show the same pattern.

Like gypsy moth, Nantucket pine tip moth and pine looper can appear anywhere susceptible trees are found, and their effects sometimes have been Cape-wide. In contrast, outbreaks of the brown-tail moth have been highly localized, occurring mostly in Provincetown, Truro, Wellfleet, and parts of Dennis and Barnstable in beach plum and rosa rugosa on sand dunes (US Department of Agriculture, 1974; McLane, 1997). Infestations of brown-tail moth pose a health concern for humans because contact with the egg masses or the hairs of the caterpillar can cause a serious rash or lung irritation. Control efforts have included aerial and ground-based applications of pesticides including DDT, methoxychlor, and Sevin dating from the 1960s through the end of the study period.

Information Sources Prior to 1970, records of pesticide application came from federal sources, since the US Department of Agriculture Animal and Plant Health Inspection Service (APHIS), Agricultural Research Service was responsible for all gypsy moth programs at that time. Records of gypsy moth control from 1920 to 1956 were obtained from the US Department of Agriculture (USDA) Otis Methods Development Center in Sandwich, MA; however, no records were available from USDA for pesticide treatments after 1956. The US Forest Service maintains a gypsy moth database where state records of gypsy moth control activities post 1970 are collected.

At the state level, an unpublished survey of MA-DEM records (and its predecessors) provided an overview of pest outbreaks and control activities for gypsy moth and other forest pests (Burnham, 1994), and additional data were extracted from MA-DEM Annual Reports. MA-DEM's facility in Stow, MA, yielded maps that were created to guide planes applying pesticides during the 1950s and 1960s. These data appeared as hand-drawn polygons on USGS quadrangle maps, with notations for pesticides applied, application rate, date(s) of application, and wind speed and direction. Another source of records was the MA Pesticide Bureau's aerial spray permit application files for 1980 to the present. These records include the means of application, the agents used, application rates, and expected dates of application, but details regarding locations treated are scant.

Interviews with tree wardens and other local officials indicate that some pesticide activities were funded directly by municipalities and are not included in the state and federal records. Interviews and our own research failed to yield town records of pesticide applications.

Cranberry Cultivation

Historical Locations of Bogs and Years of Operation Land use and hydrography coverages together provide good information about the locations of cranberry bogs where pesticides would have been used. Cranberries are the largest single crop produced on Cape Cod, and more than 500 bogs or bog complexes are mapped in the Cape Cod Study GIS. Acreage devoted to cranberry cultivation on

Table 3. Recorded instances of wide area pesticide application for tree pest control during the 1960s excerpted from 1948 to 1995 data.

Year	Target pest	Location	Treated area (acres)	Pesticide active ingredient	Application method	GIS status/map source for mapped spray areas	Data sources
1960a		Otis Air Base		Dieldrin		not mapped	f
1960b	Gypsy Moth	Truro	600	DDT		not mapped	e
		W. Barnstable	500				
		Falmouth	100				
		Mashpee	50				
1960c	Brown-tail moth	High Head, Truro		DDT		map supplied by town	m
1961a		Otis Air Base		Dieldrin		not mapped	f
1961b	Gypsy moth	Mashpee	2850	DDT		not mapped	
1962a		Otis Air Base		Dieldrin		not mapped	f
1962b		Mashpee, Falmouth, Barnstable	1200	DDT (except Sevin used around dairy and other farms)		not mapped	b
1963a		Pilgrim Lake area, Provincetown		Methoxychlor		lake mapped using MassGIS hydrography coverage	f,h
1963b		Otis Air Base		Dieldrin		not mapped	g
1963c	Japanese beetle	Otis Air Base runway and cantonment areas	2700	Dieldrin		mapped from 1992 MMR publication	i
1964a		Otis Air Base		Dieldrin		not mapped	f
1964b	Gypsy moth	mapped areas in	6670 total	6% DDT	aerial	MA-DEM USGS maps on which spray areas were delineated	b
		Falmouth	800				
		Mashpee	1090				
		Sandwich	490				
		Barnstable	2290				
		Otis Air Base	2400				
1964c	Gypsy Moth	unknown	83.6 miles, of road	3.5% Sevin	ground	not mapped	b
1965a		Otis Air Base		Dieldrin		not mapped	f
1965b	Gypsy moth	mapped areas	22,400	Sevin	aerial	MA-DEM USGS maps on which spray areas were delineated	b
1965c	Brown-tail moth	mapped areas	265	Sevin		USDA–APHIS USGS maps on which spray areas were delineated	f,l
1966	Brown-tail moth	mapped areas	439	Sevin		USDA–APHIS USGS maps on which spray areas were delineated	f,l
1967	We found no pesticide spraying records for this year						all references
1968	We found no pesticide spraying records for this year						all references
1969		Nickerson State Park		Gardona	ground	MA-DEM map	b

References: (a) USDA–APHIS, Otis Methods Development Center Records; (b) C. Burnham (1994); (c) *Cape Cod Standard Times* (5/11/49); (d) *Cape Cod Standard Times* (5/7/49); (e) MA-DEM Annual Reports; (f) Win McLane, USDA–APHIS (1997); (g) MA-DNR Annual Report (1959); (h) Richard Kelliher, retired MA-DEM employee (1997); (i) E.C. Jordan (1986); (j) DEM Region 1 Records; (k) *Cape Codder* Newspaper; (l) USDA Records, USGS quadrangle maps; (m) Cheryl Osimo Interview with Truro Officials (1996); (n) Brian Dale, Falmouth Tree Warden (1997); (o) USDA Forest Service (1973); (p) MA-DFA Pesticide Bureau, Aerial Spray Permit; (q) MA-DEM, Diplodia Tip Blight Control Study, 1981.

Note: The full table of spray events for 1948–1995, from which this table is excerpted, may be viewed at www.SilentSpring.org.

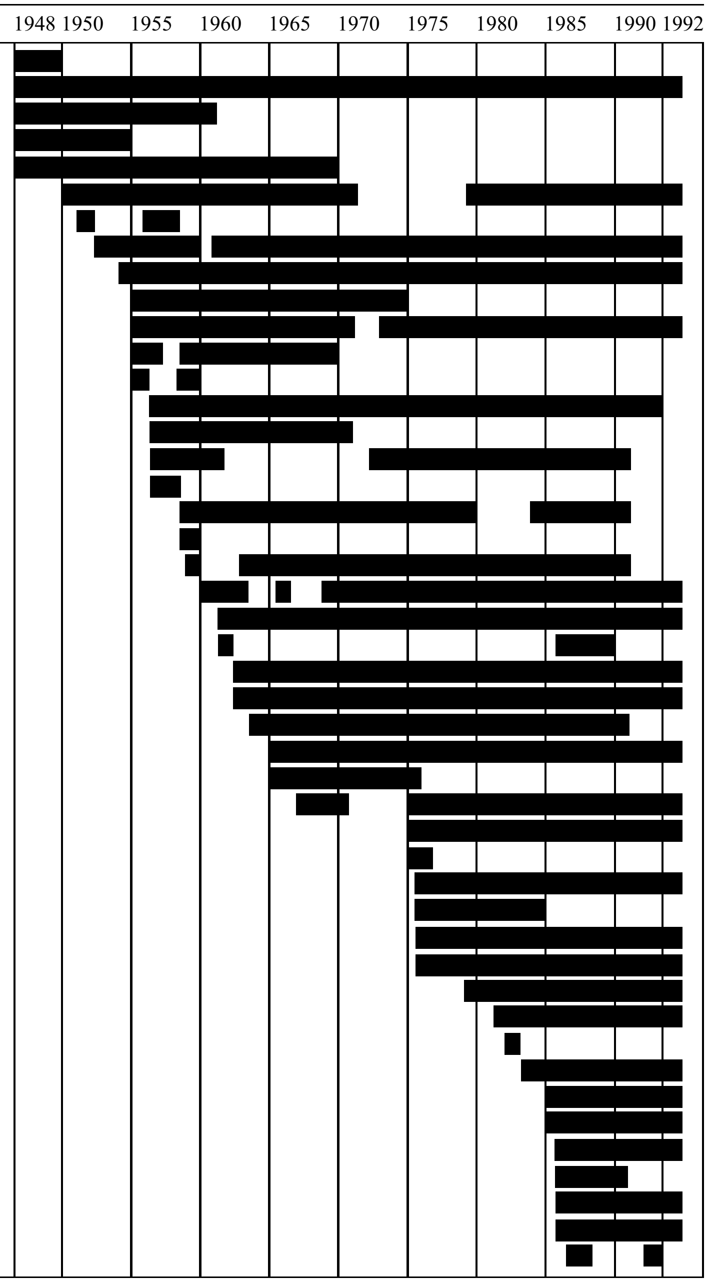
Cape Cod peaked in 1950 at 4677 acres (Massachusetts Department of Agriculture, 1957). Because land use data are mapped for four different time periods, they provide information about approximate years of operation. Historical locations of bogs may be viewed in the land use section of the *Cape Cod Breast Cancer and Environment Atlas* at www.SilentSpring.org.

Pesticides Used Given the scarcity of historical pesticide use records for specific bogs and the large number of independently managed bogs, it was not practical to research pesticide use for individual bogs, so the study relies on information about typical practices during different time periods and for both larger and smaller bogs. The University of Massachusetts Cranberry Experiment Station annual lists of pesticides approved for cranberry cultivation are shown by year in Table 4.

In the late 1800s to early 1900s, cranberry growers relied primarily on flooding and lead arsenate to control pests; and in the 1930s, cranberry growers used nicotine,

Table 4. Pesticides approved for use on cranberry bogs 1948–1992.

Active ingredient	Brand name(s)
Pyrethrum soap/dust	
Kerosene/fuel oil as agent	
Rotenone	Derris Powder
p-Dichloro-benzene	
DDT	
2,4-D	Weedar 64, Ester Brush Killer, Esteron
Ryania	
Ferbam	Fermate
Stoddard solvent	
Dieldrin	
Malathion	
Aldrin	
Heptachlor	
Parathion	
2,4,5-T	Weedone
Zineb	
Chlordane	
2,4,5-TP	Silvex, Esteron
Aminotriazole	Amitrole
Dalapon	
Diazinon	AlfaTox
Mancozeb	Manzate, Maneb, or Dithane, Penncozeb
Phaltan	Folpet
Carbaryl	Sevin
Simazine	Princep
Chlorpropham	Chloro-Ipc
Dichlobenil	Casoron
Naptalam	Alanap
Azinphos-methyl	Guthion
Piperonyl butoxide	Pyrenone
Methoxychlor	AlfaTox
Diquat	
Ethephon	Ethrel
Norflurazon	Evital
Propargite	Omite
Napropamide	Devrinol
Glyphosate	Roundup, Rodeo
Triclopyr	Garlon
Fluazifop-butyl	Fusilade 2000
Chlorpyrifos	Lorsban
Acephate	Orthene
Sethoxydim	Poast
Thiram	Royal-MH-30
Chlorothalonil	Bravo
Cupric hydroxide	Kocide
Ziram	Ziram



Source: Massachusetts Cranberry Experiment Station, Cranberry Chart Books, 1948–1992.

cyanide, and especially pyrethrum, as well as lead arsenate (Massachusetts Department of Agriculture, 1948). In general, persistent organochlorines were used between 1945 and the early 1970s when organophosphates became the major insecticide. By 1946, cryolite, rotenone (derris), *p*-dichlorobenzene, and DDT came into use. Pyrethrum was used most frequently, followed by DDT, according to a 1946 survey of Massachusetts cranberry growers (Massachusetts Department of Agriculture, 1948). Herbicides used in 1946 included kerosene, 2,4-D, ammate, sodium arsenite, sodium arsenate, iron and ferric sulfate, copper sulfate, salt, and *p*-dichlorobenzene (Massachusetts Department of Agriculture, 1948). Kerosene was the most frequently used herbicide from 1944 to the mid-1960s, while Casaran (dichlobenil) was used most from 1963 to 1984 (Terris, 1990) and continues to be used today in conjunction with devrinol. From 1946 to 1966, several insecticides were used, including pyrethrum, malathion, DDT, parathion, and dieldrin (Terris, 1990). DDT use peaked in 1953 and began to decline by 1955 because the black-headed fireworm and blunt-nosed leafhopper developed resistance (Massachusetts Department of Agriculture, 1957). Malathion was the most commonly used pesticide in 1955. Parathion had the longest period of use during the 1946–1966 period. From 1966 to 1984, carbaryl, dieldrin, diazinon, and guthion were used. Diazinon and parathion were used most frequently from 1966 to 1984 (Terris, 1990). Fungicides were used less frequently than insecticides or herbicides and included ferbam, zineb, maneb, mancozeb, difolatan, phaltan, fermate, and bordeaux mixture.

Application Methods Pesticide application methods in cranberry cultivation have evolved from ground application to aerial application and then chemigation — a method that applies pesticides *via* sprinkler systems. From 1944 to the early 1950s, most cranberry growers used ground application; but by 1955, aircraft were used twice as often as ground application (Massachusetts Department of Agriculture, 1957; Terris, 1990). In its 1968 report, the Massachusetts Department of Agriculture (1968) noted that aerial application still was dominant, followed by chemigation on 10% of acreage. By 1984, 70% of bogs were using chemigation (Terris, 1990), and in the late 1990s, about 83% of cranberry pesticide applications were by chemigation, 14% by air (helicopter), and 3% by ground application (Cranberry Institute, 2000).

Golf Course Management

Historical Locations and Years of Operation The MacConnell land use coverage identified locations of 35 golf courses, including four that date back to the 19th century. Courses were generally uniform in size and pesticide use practices. However, the amount of rough varied considerably — a finding that may be important to the

Table 5. Pesticides used on Cape Cod golf courses, 1980s–1990s.

Fungicides		Herbicides		Insecticides	
Reported name	Common name	Reported name	Common name	Reported name	Common name
Aliette[a]	fosetyl-al	Acclaim[a]	fenoxaprop-ethyl	Diazinon[b]	
Banner[a]	propiconazole	Balan[b]	benefin	Dursban[a]	chlorpyrifos[b]
Banol[a]	carbanolate	Chlordane[b]		Isofenphos[b]	
Baylaton[a]	triadimefon	DCPA[b]		MCPP[a]	mecoprop
Benomyl[b]		Dicamba[b]		Merit[a]	clomazone
Chipco 26019[a]	iprodione[b]	Dimension[a]	dithiopyr	Proxol[a]	trichlorfon[b]
Cleary's 3336[a,b]	thiophanate methyl	Glyphosate[b]		Sevin[a]	carbaryl
Cycloheximide[b]		MCPP[b]	mecoprop		
Daconil[a,b]	chlorothalonil	Oftanol[a]	isophenfos		
Dyrene[a,b]	anilazine	Pendimethalin[a]			
Formec 80[b]		Pentachlorophenol[b]			
Maneb[b]		Roundup[a]	isopropylamine salt of glyphosphate		
Mercury[b]		Siduron[b]			
Rubigan[b]	fenarimol	Trimec[a]	2,4-D, dicamba, mecoprop		
Sentinel[a]		2,4-D[a,b]			
Subdue[a]	metalaxyl[b]				
Thiram[b]					
Touche[a]					
Tridimefon[b]					

[a]Source: mid-1990s use reported in Silent Spring Institute (1997).
[b]Source: 1985 use reported in Cape Cod Commission (1990).

Table 6. Estimated relative exposure to pesticides at test addresses (n = 3916).

Pesticide exposure source	Year	Number of residential addresses[a]	Exposed addresses		Exposure intensity measure	Exposure intensity score for exposed addresses[b]			
			n	%		Minimum	Median	75th percentile	Maximum
Wetlands (mosquito control)					exposure proportional to inverse of				
Address within 400 m	1951	1288	751	58	distance squared from source (1/d^2)	0.0000063	0.000057	0.00016	0.40
	1971	2513	1424	57		0.0000063	0.000052	0.00015	0.40
	1984	3555	1843	52		0.0000063	0.000049	0.00014	0.40
	1990	3916	1982	51		0.0000063	0.000050	0.00014	0.40
Actively cultivated agriculture other than cranberry bogs					exposure proportional to inverse of distance squared from source (1/d^2)				
Address within 400 m	1951	1288	347	27		0.0000063	0.000028	0.00014	0.26
	1971	2513	321	13		0.0000063	0.000018	0.000059	0.26
	1984	3555	441	12		0.0000063	0.000018	0.000051	0.26
	1990	3916	437	11		0.0000063	0.000018	0.000051	0.26
Former agriculture cultivated during organochlorine years[c]					exposure proportional to inverse of distance squared from source (1/d^2)				
Address within 400 m	1951	N.A.	N.A.	N.A.		N.A.	N.A.	N.A.	N.A.
	1971	2513	610	24		0.0000063	0.000040	0.00040	10
	1984	3555	933	26		0.0000063	0.000054	0.00053	10
	1990	3916	1113	28		0.0000063	0.000053	0.00049	10
Active cranberry bogs					relative deposition from bogs[d]				
Address within 400 m	1951	1288	193	15		0.000010	0.0016	0.0047	9.1
	1971	2513	280	11		0.00000047	0.0015	0.0045	9.1
	1984	3555	424	12		0.00000047	0.0014	0.0039	9.1
	1990	3916	486	12		0.00000047	0.0015	0.0045	9.1
Area sprayed for tree pests[e]					relative deposition from tree spray[d]				
Address within 400 m	1951	1288	0	0		N.A.	N.A.	N.A.	N.A.
	1971	2513	167	7		0.0044	0.16	10	10
	1984	3555	240	7		0.0011	0.080	10	10
	1990	3916	262	7		0.0011	0.082	10	10
Golf courses					exposure proportional to inverse of				
Address within 40 m	1951	1288	2	0.2	distance squared from source (1/d^2)	0.00060	0.00076	0.011	0.014
	1971	2513	11	0.4		0.00060	0.00086	0.0020	0.014
	1984	3555	25	1		0.00060	0.0016	0.0033	0.014
	1990	3916	19	0.5		0.00060	0.0017	0.0033	0.014
Active railroad rights of way					exposure proportional to inverse of				
Address within 40 m	1951	1288	20	2	distance squared from source (1/d^2)	0.00068	0.0013	0.0029	0.040
	1971	2513	13	1		0.00068	0.0022	0.0039	0.13
	1984	3555	18	1		0.00062	0.0012	0.0033	0.13
	1990	3916	18	0.5		0.00062	0.0012	0.0033	0.13

[a]Number of addresses on land that was residential in each year.
[b]Relative exposure intensity scores normalized to theoretical maximum of 1 for residences outside the source area for each exposure source category; exposure scores set to 10 for residences inside the sources areas.
[c]Excludes cranberry bogs; organochlorine years are 1948–1974.
[d]Relative deposition estimated by modeling spray conditions (see text).
[e]Does not include Cape-wide spraying in 1948–1950 and 1955.

extent that rough may provide a barrier to pesticide drift or dispersion from the golf course to neighboring residences.

Pesticides Used and Application Methods A variety of insecticides, herbicides, and fungicides were used for turf management on golf courses. Table 5 lists pesticides reported by Cape Cod golf course superintendents in 1997 (Silent Spring Institute, 1997) and those used on selected Cape Cod courses in the mid-1980s (Cape Cod Commission, 1990). Pesticides were typically applied by ground rather than aerial methods. Based on 1997 interviews, fungicides were the most commonly used chemicals. Baylaton, Chipco 26019, Cleary's 3336, and Daconil were the most frequently reported. Fungicides were typically applied preventively on greens and, at some courses, on tees. The annual frequency of applications was variable. At courses where tees and fairways did not receive annual preventive applications, they received spot treatment on an "as needed" basis. Roughly equal amounts of insecticides and herbicides were used. The brands mentioned most often were Dursban and Merit. About half of the courses reported preventative applications, while the others used spot treatment on an "as needed" basis. Interviews indicated that insecticides were rarely used on "rough" areas, although herbicides were used there.

Information Sources Information about the number of years of course operation; acreage estimates for greens, tees, fairways and rough; and pesticide use practices was obtained from golf organizations and course superintendents. None of the superintendents reported that they maintain pesticide use records.

Other Pesticide Uses

For other pesticide uses, including agriculture other than cranberry bogs, rights-of-way management, and mosquito control, locations were identified; but typical pesticide use practices could not be established. Locations of agriculture other than cranberry bogs and rights-of-way were mapped in the GIS, as described previously. Officials of the Cape Cod Mosquito Control Project (CCMCP), which represents all Cape Cod towns, reported that all Cape Cod wetlands were sprayed for mosquito control (Silent Spring Institute, 1997). DDT was used beginning in the 1940s. Methoxychlor came into use in the 1950s and 1960s, and abate (temephos) in the 1960s and early 1970s. Use of biological controls (*B. thuringiensis*) began in the early 1970s. Aerial spraying typically was not used for wetlands of less than 5–10 acres. In 1992, CCMCP established a computer-based GIS and annual reporting that includes the location, date, pesticide used, and application method for mosquito control activities (Silent Spring Institute, 1997).

Analysis of Test Addresses

Results of the test address analysis show geographic variation in estimated pesticide exposures. These results are shown in Table 6. Results may also be mapped to show the geographic distribution of exposed and unexposed addresses and of exposure intensities.

As shown in Table 6, residence near wetlands sprayed for mosquito control is likely to be the most common exposure, affecting about half of addresses throughout the study period. Exposure from actively cultivated agricultural land other than cranberry bogs declines over the study period from 27% of addresses in 1951 to 11% of addresses in 1991. Exposure in later years to land that was agricultural during the years of persistent organochlorine use is also of interest because these compounds remain in the environment, and results show that approximately one fourth of test addresses fell within the exposed areas, defined as less than 400 m from land that was agricultural during the organochlorine years. For exposure from active cranberry bogs, the proportion of addresses within 400 m of a bog is roughly stable at 12–15% throughout the study period. All addresses were affected by gypsy moth spraying in 1948–1950 and 1955, and 7% of test addresses also were affected by tree pest applications in other years. Pesticides from golf courses and rights-of-way are unlikely to affect many subjects, with fewer than 5% of addresses exposed. Roughly half of the addresses classified as exposed to active cranberry bogs or agriculture other than bogs were separated from these sources by a forest buffer that may reduce exposure from drift.

Examining exposure intensity scores (see Table 6) shows that, for many exposures, minimum scores were quite low, relative to maximum scores, varying by four to six orders of magnitude. These results indicate that addresses classified as unexposed are appropriately defined, while some addresses with very low exposures are classified as exposed. Substantial differences between the 75th percentile and maximum scores indicate that a relatively small percentage of test addresses have distinctively higher exposures than are typical. Exposure from tree pest spraying is an exception to this pattern, with test address results showing the top quartile of addresses at the maximum score assigned to homes inside the spray area.

Discussion

This research extends the application of GIS technology in a study of health effects of individual-level exposures to pesticides applied for multiple uses over a 50-year period since the beginning of the organochlorine era. While previous studies have used GIS-based distance and direction measures to assess health effects from large-scale monoculture agriculture, this study of Cape Cod reconstructs complex historical exposure patterns from smaller areas where pesticides were applied for tree pests, mosquitoes, cranberry bogs, other agriculture, golf courses, and rights-of-way during an era of rapid development, with residential land adjacent to, or developed on, historical pesticide use areas.

Systematic interviews and focus groups led to identification of written pesticide use records. The goal was to reconstruct spatial, temporal, and intensity or "dose" information. Given the expected limitations of historical records, the focus was on assessing relative intensity, i.e., on correctly ranking higher and lower exposures and differentiating exposed from unexposed. Federal and state records were most useful; towns were typically not able to provide records. For some tree pest control programs, records include mapped application areas, identification of specific pesticides used, and information about application rates and methods, whether aerial or ground-based. These records come closest to meeting the goals for GIS in health studies to include spatial, temporal, and intensity information (Vine et al., 1997). However, for many tree pest control activities, application areas could not be mapped within towns, or other information was missing. For cranberry bogs and golf courses, spatial and temporal information may be regarded as reasonably complete. Records of specific chemical use at specific sites were not identified, but exposure reconstruction was informed by substantial information about typical or approved practices. For agricultural land and rights-of-way, spatial and temporal information is also reasonably complete, but assessment of chemical use for each time and place was beyond the resources of this study. For mosquito control, use of wetlands as a proxy for spray locations is less satisfactory than the land use categories for agriculture and likely results in greater misclassification of exposed and unexposed addresses. Expert interviews provide a broad picture of typical mosquito control practices.

New GIS programming was developed to incorporate transport modeling of pesticide drift for exposures from aerial applications for tree pests or on cranberry bogs where the underlying data are adequate to support this refinement. Huang and Batterman (2000), in a recent review of 45 epidemiological studies that used residence location as a measure of exposure to air pollution, recommend the use of modeling to reduce exposure misclassification that leads to nonsignificant findings.

Results of this investigation document a history of substantial use of persistent organochlorines on Cape Cod in 1948–1974 and other pesticides from the mid-1970s through the 1990s. Although nearly all areas of the Cape were sprayed with DDT in 1948–1950 and 1955, results show geographic variation in exposure intensity within Cape Cod in other years. Establishing both substantial pesticide use and variation in geographic location and intensity of use within the Cape is important because these conditions are prerequisite for applying this exposure assessment in an epidemiologic study.

Limitations Due to Missing Data

Missing data were identified as a serious limitation. Lack of more detailed information about mosquito control is of particular concern, given that more than half of the test addresses were classified as exposed. In addition, information gathered in this study indicates that some wide area pesticide applications, particularly town and private spraying for tree pests, remain unrecorded and unmapped. While the focus in this study was on reconstructing exposure at the individual level, pesticide application events that were recorded at the town level, but not mapped, could be used to create town-level exposure variables. These ecologic variables would result in overestimating exposure for some addresses, while avoiding the underestimate of exposure that results from excluding the ecologic data.

Evidence of missing data, particularly for mosquito and tree pest control, raises questions of whether relative exposure measures derived from the Spatial Proximity Tool correctly rank higher and lower exposure of individual addresses and whether there is a meaningful "unexposed" group. These problems of exposure misclassification are common in environmental epidemiology but nonetheless remain serious barriers to identifying health impacts of pollutants. A program of surface soil sampling to compare measured levels of persistent pesticides and their degradation products with levels predicted by the GIS exposure assessment would provide information about whether the GIS variables correctly assess relative historical exposures. This work is currently underway.

GIS as a Tool to Optimize Exposure Indicators

Given that limitations due to missing exposure information, such as those we found in this study, are typical in retrospective environmental health studies, GIS may be seen as a tool for creatively, but judiciously, constructing proxies and developing methods for estimation and interpolation. Simple spatial exposure measures, such as distance to agricultural land use, may result in substantial misclassification that tends to bias environmental health studies toward null results, while complex fate and transport exposure models are resource-intensive, limiting the range of environmental factors that can be studied within funding and time constraints. In addition, historical data sets required for input to the models may have so much uncertainty and missing information that elaborate exposure modeling cannot improve on simpler methods. GIS technology offers flexible capabilities across the full range from simple proxies to complex modeling, allowing researchers to seek an optimal balance along this continuum by efficiently and systematically incorporating multiple environmental parameters. The development and application in this study of the Spatial Proximity Tool to integrate pesticide drift modeling with local meteorological data, information about pesticide use practices, and locations of spray areas and residences, represent an application of GIS along the middle ground of the continuum.

Table 7. Internet site locations for pesticide use information.

Site name	Location
US EPA	http://www.epa.gov
Office of Pesticide Programs	http://www.epa.gov/pesticides/
EPA Databases on Actual Usage of Pesticides	http://www.agnic.org/agdb/epadbpst.html
Pesticides in Groundwater Database	http://www.epa.gov/opptintr/cbep/actiocal/pgd.htm
Organophosphate Use Information	http://www.epa.gov/oppbead1/matrices/
THERdbASE Exposure Assessment Software	http://www.epa.gov/nerlesd1/therd/therd-home.htm
USGS	http://www.usgs.gov
Pesticide National Synthesis Project	http://water.wr.usgs.gov/pnsp/
National Water Quality Assessment Program	http://water.usgs.gov/nawga/
USDA	http://www.usda.gov
Agricultural Chemical Usage	http://usda.mannlib.cornell.edu/reports/nassr/other/pcu-bb/
US Forest Service Gypsy Moth Control Database	http://fhpr8.srs.fs.fed.us/wv/gmdigest/gmdigest.html
California Department of Pesticide Regulation	http://www.cdpr.ca.gov/index.htm
The National Center for Food and Agricultural Policy	http://ext.agn.uiuc.edu/data/ncfap.html

Resources for Other Studies

For future studies, researchers may benefit from additional data resources, including both state and local records and national resources, which have grown tremendously over the last 5 years. Table 7 lists useful websites, emphasizing national resources. The US EPA Office of Pesticide Programs provides information about pesticide formulations, labels, restrictions, and usage, and online records of organophosphate use by region, crop, and pesticide. The EPA Outdoor Residential Exposure Task Force (ORETF) is developing a database for both professionals and nonprofessionals (homeowners) exposed to pesticides applied to residential lawns. The Pesticide Use Program within the National Center for Food and Agricultural Policy (NCFAP) maintains a database of over 15,000 individual records that quantify the use of specific active ingredients by crop and state, including estimates for 200 active ingredients used on 87 crops during the 1990s. The US EPA Pesticides in Groundwater Database collects monitoring studies conducted by federal, state, and local agencies, encompassing monitoring data from over 65,000 wells starting in 1971. The USGS National Pesticide Synthesis Project focuses on pesticides in the streams, rivers, and groundwater of the US and provides annual pesticide use maps by county.

Though the US EPA and USGS are the largest single sources of information, other agencies provide information about pesticide use on regional, state, or local levels. The US Forest Service maintains a gypsy moth control database. Starting in 1990, the National Agricultural Statistics Service, Agricultural Statistics Board, USDA compiled pesticide application rates per year by specific crop or use category. In 1997, the USGS, in cooperation with the New York State Department of Environmental Conservation, began collecting monitoring data on pesticides in the state of New York. California has required pesticide use reporting by township since 1990 (California Environmental Protection Agency, 1995), including data on the pesticide used, amount applied, and location at a resolution of approximately 1 square mile. This database was used in the study of fetal death described earlier (Bell et al., 2001).

Public Information and Public Policy Implications

In addition to assessing exposures for the Cape Cod Breast Cancer and Environment Study, maps and other data collected in this study also serve public information and public policy goals. Maps of pesticide use areas alert residents and planners to potential impacts on groundwater, which is the source of drinking water for Cape Cod residents, and inform decisions about future land use on previously treated land. Maps and related data may be viewed at www.SilentSpring.org and additional data are available from the study team.

In addition, the Cape Cod Study GIS provides an example of the development of environmental data infrastructure that parallels the disease surveillance infrastructure represented, e.g., by state cancer registries. Environmental data could, in some instances, be used in preference to health surveillance data to identify promising geographic areas for environmental health studies, and the Pew Environmental Health Commission HealthTrack program has recently proposed development of environmental exposure databases as a national public health priority (Pew Environmental Health Commission, 2000; Wakefield, 2000).

Future Research

Future steps in the Cape Cod Study will include additional aggregation procedures to sum exposures across all of the Cape Cod addresses where each study subject lived and across all of her years at each address.

GIS measures reported here will be used in the case–control epidemiologic study of 2100 women in conjunction with self-reported occupational history and home and lawn pesticide use, and GIS-based measures of pesticide impacts on public drinking water wells. In addition, future research will evaluate the concordance between GIS exposure estimates and environmental and biological measures of pesticides, including approximately 75 soil samples and environmental measurements of household dust, air, and women's urine for 120 homes in the case–control study. None of these measures approaches the ideal of historical biological exposure assessment, which, indeed, cannot be attained retrospectively. However, together, the measures in the Cape Cod Study contribute to an exceptionally rich picture of pesticide exposure in a geographic region with a history of large-scale pesticide uses and elevated breast cancer incidence that is unexplained by established risk factors.

This research represents an approach to measuring pesticide exposure that has not previously been used in a breast cancer study; and it offers the opportunity, although limited by various sources of exposure misclassification, to assess exposures dating back to the etiologic period for a disease characterized by long latency and perhaps affected by exposures at specific stages of the life cycle (e.g., the interval between menarche and first full-term pregnancy). The exposures assessed here may also be used in studies of other health outcomes on Cape Cod and methods may be applied in other geographic regions. These methods have the potential to contribute substantially to environmental epidemiology in future years as mapped environmental data become increasingly accessible through state, federal, and private sector GIS programs. With development and validation of these new data resources, GIS can facilitate investigation of environmental impacts on health in large populations.

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