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GIS AND DISEASE

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■ **Abstract** Geographic information systems (GIS) and related technologies like remote sensing are increasingly used to analyze the geography of disease, specifically the relationships between pathological factors (causative agents, vectors and hosts, people) and their geographical environments. GIS applications in the United States have described the sources and geographical distributions of disease agents, identified regions in time and space where people may be exposed to environmental and biological agents, and mapped and analyzed spatial and temporal patterns in health outcomes. Although GIS show great promise in the study of disease, their full potential will not be realized until environmental and disease surveillance systems are developed that distribute data on the geography of environmental conditions, disease agents, and health outcomes over time based on user-defined queries for user-selected geographical areas.

OVERVIEW

The geography of disease, an important component of medical geography, comprises the spatial analysis of pathological factors (causative agents, vectors, hosts, reservoirs, and people) and their relationships to geographical environments (physical, cultural, and biological) (35, 46). The medical geographic approach to the study of disease has not been the dominant perspective in the United States. Nevertheless, efforts to map the spatial distribution of human cases of disease and the geography of environmental risk at local, regional, and even global scales have been made again and again throughout our history (45, 47, 62, 66). The development of geographic information systems (GIS), computer-based systems for integrating and analyzing spatially referenced data, has provided new tools for medical geographic research on disease. GIS and related technologies such as remote sensing are enabling technologies (22, 38), applicable in many academic disciplines and professions and adopted in some of these well before the earliest applications in public health. Recent books describing public health applications of GIS in the United States (21, 48) and the other contributions on GIS published in this volume suggest that the diffusion of GIS into health research and public health practice has moved beyond the early innovation phase.

This review identifies and summarizes selected studies using GIS or remote sensing to investigate disease, primarily in the United States. Information on health applications of GIS can be found in an extraordinarily wide range of sources including general, specialized, and multidisciplinary journals on public health, medicine, environmental science, social science, and geographic information science, conference proceedings, government documents from all levels, and studies conducted by community-based groups. Nevertheless, many applications, particularly those developed by health services providers, insurers, and management companies or state and local public health agencies, may never have been described in the literature. To develop the organizing framework for this review, disease is considered in terms of a hazard-exposure-outcome process (67). The first section of the review surveys GIS research on the sources and distribution of disease agents. This section includes research on the sources and distribution of environmental contaminants and biological agents and briefly considers the effects of environmental conditions on biological agents. The second section of the review considers how GIS are being used to investigate exposure to disease agents. This includes the role GIS can play in assessing environmental quality, modeling different exposure mechanisms, and documenting environmental inequities (differential exposure to agents based on race and class). The third section examines studies that describe and analyze the geographical distribution of health outcomes alone and studies that attempt to integrate and analyze information on all stages in the hazard-exposure-outcome process.

GIS applications require digital spatial databases. For this reason, they very much reflect the quality and availability of data on disease hazards, exposures, and outcomes. The final section of the review considers this crucial link between environmental and disease surveillance systems and GIS-based analyses of disease. Weaknesses in existing and proposed surveillance systems are identified and the contributions that geography and GIS technology can make to strengthen environmental and disease surveillance systems are discussed.

SOURCES AND DISTRIBUTION OF DISEASE AGENTS

Agents causing disease can be physical, chemical, or biological. Two approaches are used to describe the presence and distribution of these agents in the environment. First, the sources of manufactured agents can be identified, including the quantities produced, stored, and shipped from the sites and the eventual disposition of the releases, termed "fate and transport" in the environmental literature. Second, the environment can be monitored to detect the presence of naturally occurring or manufactured causative agents. GIS analysis has supported both approaches, although different approaches have been emphasized in the study of environmental contaminants and biological agents.

Environmental Contaminants

Some of the earliest GIS applications with implications for the study of disease involved mapping point sources releasing toxic chemicals into the environment

(65). The Agency for Toxic Substances and Disease Registry (ATSDR) was an early supporter of the use of GIS in environmental health studies, adopting the technology in 1990 and sponsoring a workshop on GIS applications in public health and risk analysis in 1994, underscoring its commitment to GIS as a tool for assessing "real risks to real people" (1). The availability of data from the Toxics Release Inventory (TRI) developed by the Environmental Protection Agency (EPA) in 1986 has supplemented pollution disclosure data mandated at the state and local levels. Grounded in the "right-to-know" perspective on threats to human health, a mapping program to display sources of chemical hazards using computerized street maps based on the U.S. Census TIGER/Line files was distributed on the TIGER/Line 1992 CD-ROM product as LandView (71).

TRI data continue to be used in simple GIS applications that map TRI sites in relation to activity sites like schools (2). It is now much more likely, however, that information on environmental contamination is integrated with population or human health outcome data in a GIS. Studies limited to modeling the sources and distributions of environmental agents have themselves evolved. GIS are being used to implement EPA recommendations for managing sources of groundwater contamination in wellhead protection areas (32), integrating data from a variety of sources on the distribution of agents. The transportation of hazardous substances like nuclear waste has been considered in applications that map routes (25); modeling of nonpoint sources of pollution has also been addressed in GIS applications. Nonpoint source pollution from agriculture is an important factor affecting water quality. Parameters of runoff models developed for individual watersheds may not be transferable to other watersheds where comparable data for calibration are not available. Integrating hydrological models and GIS has increased model portability, improving nonpoint source modeling at the watershed scale (41).

Environmental contaminants occur both naturally and as a result of human activity. GIS analysis has been used to assess the relative contributions of naturally occurring contaminants versus those of human origin. In a study of arsenic concentrations in water drawn from 173 wells producing from the Ogallala Aquifer in an agricultural region of west-central Texas, a GIS was used to map and evaluate arsenic concentrations (34). Arsenic compounds were applied to cotton fields in the area, as in many other agricultural areas in the United States, but arsenic was also present in local rock formations. The evidence supported pesticide use rather than local rock formations as the source of arsenic in high-concentration samples. Higher levels were observed at shallower water table depths. Other agricultural chemicals were present in high-concentration samples. Low arsenic levels were observed in groundwater samples from potential arsenic-bearing formations, and hydraulic head differentials between the Aquifer and likely arsenic-bearing formations were not compatible.

A pilot study of carcinogens in water drawn from domestic wells in Anne Arundel County, Maryland, used a GIS to determine which wells to sample (5). The GIS application identified areas potentially at risk for contamination based on commercial and industrial land use associated with volatile organic compounds, agricultural land use associated with pesticides, and geological formations associated with contaminants such as radon. Untreated water samples were drawn from wells in these targeted areas. Analysts visited the areas to verify land use, to interview residents, and to obtain permission to draw samples.

Ironically, environmental contamination may result from efforts to improve water quality through treatment. An analysis of tap water sampled in Harris County, Texas, combined statistical analysis of sampling data with GIS to assess the concentration of aluminum sulfate (alum) used as a coagulant in water treatment at several sources within the system (13) (see Figure 1). Peak concentrations were associated with source water treated with alum and were more than twice as high as the concentration currently recommended for public drinking water supplies; mean concentrations were greater than in water treated with a different coagulant.

Biological Agents

Investigating the sources and geographical distribution of biological agents of disease using GIS has proven more difficult than modeling environmental sources, primarily because of data limitations. Air and water quality monitoring systems

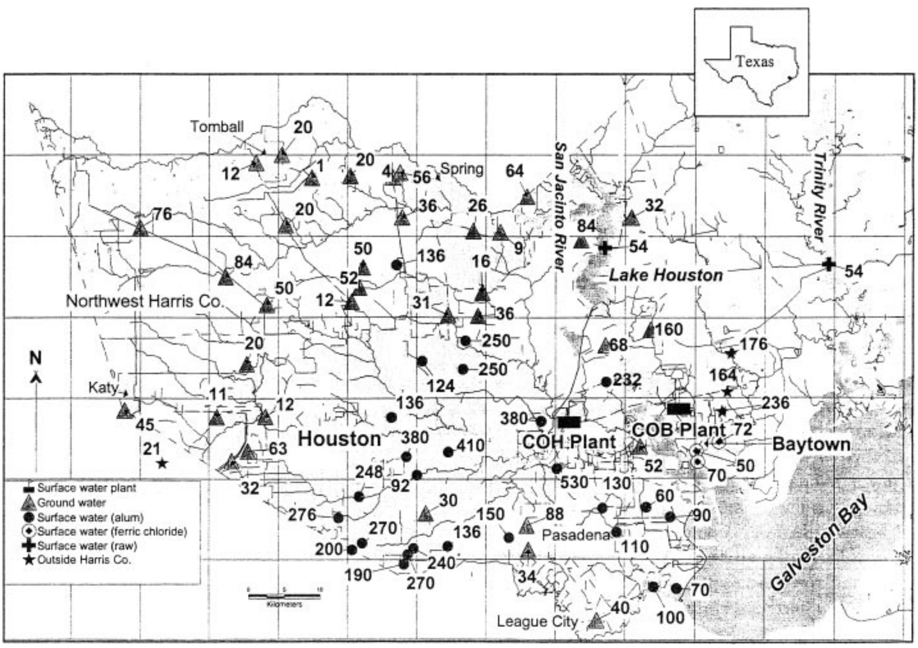

Figure 1 Concentration of total aluminum (μg/l) in tap water, City of Houston-Harris County, Texas, July 1998. Also shown are waterways and surface water treatment plants in Harris County. Reprinted from *Water Research*, Vol. 34, No. 10, Cech & Montera, "Spatial variations in total aluminum concentrations in drinking water supplies studied by geographic information systems (GIS) methods," pp. 2703–12, Copyright 2000, with permission from Elsevier Science (13).

have traditionally emphasized monitoring physical and chemical properties rather than detection of biological agents. Indeed, the presence of these agents is often determined after the fact of a disease outbreak.

Microbiological monitoring frequently occurs in coastal areas. An analysis of the number, type, spatial distribution, and costs of microbiological monitoring in southern California marine waters used global positioning systems (GPS) techniques to locate 576 sampling sites administered by 21 programs and GIS to estimate geographic coverage of each site (61). More than 87,000 tests on samples drawn from these sites were performed on an annual basis. Most of the monitoring effort occurred along the shoreline near high-use sandy beaches and storm drain and creek outlets. These sites covered about 7% of the total shoreline.

Concern over biological warfare, apparent in the literature even before the anthrax cases in 2001, has raised interest in detection of airborne biological contaminants. A variety of molecular recognition techniques are being developed for biowarfare agents and other pathogens (37) and the genetic fingerprints of microbial flora in environmental air samples taken in Korea, Kuwait, and Bahrain have been bar coded to support rapid assessment of biological material in future samples (11). The locations of biological monitoring devices could be linked to a GIS to provide a system for detecting and mapping the spread of biological contaminants.

In the case of infectious diseases transmitted directly from person to person, unlike diseases transmitted through air and water, monitoring the distribution of the causative agent is essentially reduced to surveillance of people who carry the disease. This is controversial because of threats to privacy and confidentiality and also because health service providers and their business partners have a proprietary interest in administrative records. Over the past several decades, administrative data rather than data from publicly maintained disease surveillance systems have been an important source of data on population morbidity (74), but only for those who have access to the data. Because there are geographical differences in the availability and utilization of health services, the underlying spatial pattern of morbidity in the population may not be accurately captured in these data.

Monitoring the distribution of vector-borne disease agents is complicated by the maintenance and transmission of those agents in complex and regionally variable ecological systems involving the agent, hosts, reservoirs, and vectors. As with other infectious disease surveillance programs, support for vector surveillance was reduced during the 1970s and 1980s when the associated diseases were not of major public health interest.

At the same time that availability of the TRI and Census TIGER/Line files stimulated environmental health applications of GIS, the emergence or re-emergence of vector-borne infectious disease (76) provided the impetus for early GIS applications investigating vector-borne infectious disease (29). The strong connection between vector and host distribution and environmental factors reinforced this movement because environmental management was one of the first fields where GIS technology was applied. Vector surveillance is time-consuming and expensive. Baseline data sets documenting spatial and temporal extent of vectors are rarely available. As noted by Ginsberg (28), many tick collection studies undertaken to support research on Lyme disease represented the first reported collection from those study sites.

For this reason, scientists studying the distribution of vector, host, and reservoir populations have turned to remote sensing data and GIS to model the environmental conditions conducive to these populations. Remote sensing techniques, including aerial photography and satellite sensors, analyze and interpret data gathered by means that do not require direct contact with the object. Sensors detect electromagnetic energy reflected or emitted from objects on the Earth's surface. Digital image-processing techniques are used to convert these spectral signatures into a geographic database describing land cover and other characteristics of the physical environment. The spatial resolution varies depending on the data source. Like studies of environmental contaminants, GIS analyses of vector-borne disease have become more sophisticated, incorporating more data and applying statistical and spatial statistical methods to analysis of the data at all scales (39).

A study of mice infected with the Sin Nombre virus found combinations of environmental variables that could accurately predict the infection status of mice 80% of the time (6). Landsat Thematic Mapper data were used in this study. These data have a spatial resolution of 30 m but sensors can now provide higher spectral and spatial resolution data, and the costs for acquiring these data are falling dramatically (4, 33). With remote sensing data and GIS analysis in the Sin Nombre study, vegetation type and density derived from satellite data and elevation, slope, and hydrology were assessed for 144 field observation sites along the Nevada-California border (Figure 2). Deer mice trapped at these sites were tested to determine current or past infection with the virus, and field sites were subsequently classified as positive or negative. Discriminant analysis was used to examine the relationships between the environmental variables and site infection status.

Surface temperature is another variable believed to reflect global climate change and specific climate events like the El Niño southern oscillation have implications for vector distribution. The National Oceanic and Atmospheric Administration's Advance Very High Resolution Radiometer (AVHRR) provides data that have been used to map changes in the mean land surface temperature across North America (59). Data on land and sea surface temperature have been used widely in GIS studies of vector-borne disease process in tropical areas (31, 43).

An important issue in the use of GIS analyses to assess environmental distribution of vectors is the degree to which vectors respond to environmental factors beyond the body of the host (63). The distribution and abundance of *Ixodes scapularis*, a Lyme disease vector, was studied by inspecting small mammals for ticks and by collecting questing ticks at 138 sites in state parks and other areas in Wisconsin, Illinois, and the Upper Peninsula of Michigan (30). A GIS was used to develop a habitat profile for each site. Tick presence and abundance varied, even when the host population was adequate (Figure 3). Discriminant analysis was again used to assess combinations of environmental variables that distinguished between positive and negative tick sites. Soil order and land cover were the dominant variables explaining tick presence. This and other efforts to model environmental risk highlight the importance of comparing the distribution of modeled risk areas to agents, vectors, and hosts or to the distribution of human cases and preferably to both (44, 54).

When there is a relatively short interval between exposure and onset of infectious disease, human case data have also been used alone to provide evidence of the underlying distribution of the disease agent. The National Lyme Disease Risk Map published by the Centers for Disease Control and Prevention was developed using human case data (15). Although this map was based on four years of human case data for the entire country, other mapping projects have covered longer time periods. In Russia, a GIS is being developed as the second step in a project to document stable anthrax sites in the Russian Federation (19). The first part of the project involved collection of data on more than 10,000 known anthrax foci or centers of origin identified over the past 100 years, including village name, agricultural council, region, oblast, and year of occurrence and publication of a register of sites. In the second step, the GIS will be used to integrate data from the register with databases of natural geographic features and to analyze anthrax distribution using standard GIS and statistical analyses.

We are learning that too little attention has been paid to the sources of biological agents of disease, given the rising threat from biological weapons and the inherent risks of genetics research programs. Biological materials are being manufactured, stored, and transported, but there are few sources of information on the locations where these activities are taking place and their routes and modes of transportation. Almost every article on the outbreak of West Nile virus in New York in 1999 has stated that this was the “first introduction” of the flavovirus in the Western hemisphere (55). Many comment that the mechanism of the introduction is unknown (27), although speculation has focused on migratory birds (56). Yet, in 1994, evidence presented at a U.S. Senate hearing on dual-use exports to Iraq and their impact on the health of Persian Gulf War veterans indicated that the United States exported West Nile virus to Basrah, Iraq, on May 21, 1985 (20), 14 years before its first “detection” in the Western hemisphere. Along with other biological materials including anthrax, botulism, tetanus, and brucella, the virus was supplied by the American Type Culture Collection and exported to agencies of the government of Iraq under an export license issued by the U.S. Commerce Department. The likelihood that the anthrax that killed people in the fall of 2001 came from a laboratory underscores the need for more information about the locations of these facilities and the nature of the materials stored there. In contrast to the approach for monitoring chemical contaminants, a “right-to-know” perspective on the storage, use, and transportation of biological hazards has yet to emerge. By December 2001, the President had granted the Secretary of Health and Human Services the power to classify information as secret (49). If spatial databases on the locations of biological materials are not compiled or are not accessible, the application of GIS to the study of associated diseases will be limited.

Effects of Environmental Conditions on Biological Agents

As the efforts to model the distribution of biological agents become more sophisticated, an important opportunity is presenting itself to assess the effects of environmental conditions on agents of disease. A growing body of research suggests that infectious agents may be partly responsible for some chronic health problems such as arteriosclerosis (26). Documenting how environmental conditions, human behavior, and infectious agents work together to cause disease is a challenging task.

It is increasingly difficult to separate the "natural" from the "built" environment. The condition of soils, temperature change, and habitat diversity are all fundamentally affected by human activity as well as natural processes. Yet, "there are few studies that adequately address the potential health effects of climate variability in combination with other stresses such as overfishing, introduced species, and rise in sea level" (60, p. 211) or investigate whether the efficiency of a disease transmission cycle increases with decreasing habitat diversity. It is not yet clear what role GIS analyses might play in basic research to answer these questions.

EXPOSURE TO DISEASE AGENTS

Assessing Exposure

Once there is evidence that disease agents are present in the environment, the question of the degree to which human populations are exposed to these hazards is raised. Increasingly, GIS exposure studies recognize that individuals circulate in the environment and exposure can occur at locations other than the primary residence (7). In an innovative study of exposure to air pollution in Roxbury, Massachusetts, a community-based pilot project measured concentrations of fine particulate matter and polycyclic aromatic hydrocarbons in the summer of 1999 (42). Community members carried portable monitors as they walked on streets within a one-mile radius of a large bus terminal. Data from the monitors were entered into a GIS along with data on site characteristics so that concentrations could be analyzed. The preliminary results showed promise, and the study demonstrates that pollution concentrations in areas where people circulate can be measured with limited monitoring equipment. A more comprehensive monitoring protocol could be developed to improve exposure assessment.

There may be multiple pathways of human exposure associated with the spread of contaminants. As one component of a project to study these pathways, research on off-site migration of polychlorinated biphenyls (PCBs) affecting a Native American community settled in New York, Ontario, and Quebec along the St. Lawrence River used GIS to estimate PCB concentrations in surface soil (36). Seven different methods to estimate the concentrations based on 119 samples were applied and the results were compared using a method of cross validation. All methods performed well in predicting PCB concentrations except in areas near sampling points that formed the outer boundaries of the sampling distribution.

Given the long latency periods between exposure and the detection of certain health outcomes like cancer, environmental and biological samples taken at the time a disease problem is identified do not usually represent historical exposure levels. GIS have been used to reconstruct these patterns. To estimate exposures from pesticides on Cape Cod between 1948 and 1955, information on large-scale pesticide applications to control gypsy moths and mosquitoes, to support cranberry bog cultivation and other agriculture, and to manage recreational areas and rights-of-way was obtained and incorporated into a GIS (10). Size of the application area, application method (ground or aerial), nature of the pesticide, distance and direction from application area to residence, and local meteorological data were analyzed to estimate the relative intensity of past exposure at the address of each study subject. These estimates were used with interview data to develop as complete an exposure assessment as possible, but important data gaps were also identified.

For a population-based epidemiological study of non-Hodgkin's lymphoma in central Nebraska, historical Farm Service Agency records provided ground reference data for classifying a satellite image produced in late-summer 1984 to identify crop species in a three-county area in south-central Nebraska (75). The locations of residences included in the population-based study were overlayed on crop maps using a GIS. Of the 85% of residences that could be located, 22% were within 500 m of one of the major crops grown in the study area. This distance is in the middle of the range of drift effects from pesticide applications. Crop-specific probabilities of pesticide use were calculated based on the available data. With the proximity data, zones of potential exposure could be identified. In this study, the feasibility of using remote sensing data and historical records in a GIS to reconstruct past spatial patterns of crops was demonstrated. This information was, in turn, used to assess potential exposure to pesticides.

GIS coupled with fate and transport models can also be used effectively to identify areas where people could be exposed to an accidental or intentional release of contaminants or biological agents in the future. In a study conducted in Hillsborough County, Florida, a major metropolitan county, areas potentially exposed to accidental releases of hazardous substances were identified (18). The number and type of schools and school children potentially exposed to multiple releases of hazardous chemicals were assessed using GIS. A significant negative association was observed between potential exposure levels and school enrollment, indicating fewer children in regions that could be most seriously affected. This research illustrates that GIS exposure studies can be used to assess environmental conditions for particular demographic and socioeconomic groups within the population.

Environmental Equity

Numerous empirical studies have been conducted to investigate whether minority and low-income populations are disproportionately exposed to pollution, and GIS have clearly played a role in these studies. In a study using 1990 Census population data and 1995 TRI data for the City of Minneapolis, two proximity measures commonly used in GIS-based assessment of environmental equity were used to evaluate potential exposure to airborne chemicals for minorities, the poor, and children (64). A geographic randomization methodology was developed to assess the significance of the results derived from the proximity measures.

Environmental inequity studies are beginning to explore more fully the relationships between concentration of TRI facilities in particular neighborhoods and the degree of hazard associated with those facilities. A GIS-based environmental equity study conducted in Oregon employed both a media-specific chronic toxicity index based on oral toxicity and a separate index based on total mass (53) because different chemicals ranked as the top five chemicals released statewide based on the chronic index than the chemicals ranked as the top five based on total mass. The results of the study indicated that TRI facilities were disproportionately located in minority and low-income neighborhoods but no relationship was observed between the hazard ranking of facilities given their releases and the demographic and socioeconomic characteristics of their neighborhoods.

GEOGRAPHICAL PATTERNS OF HEALTH OUTCOMES

Federal health agencies in the United States have long been involved in the preparation of atlases to display the spatial distributions of health outcomes. These projects are now taking advantage of advances in computer-assisted cartography, GIS, and online mapping (14, 23, 52). Some of these directly address disparities by racial and ethnic groups (3, 12).

Other research has used GIS in disease applications encompassing the hazard-exposure-outcome process. Research conducted in San Diego explored whether residence near highly traveled roads was associated with asthma in children from low-income households (24). The locations of residences of 5996 children 14 years old or younger diagnosed with asthma in 1993 were compared to a random control group of children with nonrespiratory diagnoses including 2284 diagnoses. The number of medical care visits made by children with asthma was also evaluated in relation to traffic levels. Traffic counts at the highest traffic street, the nearest street, and all streets within a 550-ft buffer around the residence were calculated from available traffic data. Analysis of the distribution of cases and controls by quintiles and 90th, 95th, and 99th percentiles showed no significantly elevated odds ratios. Among children with asthma, however, children whose nearest street had high traffic flows were more likely than children whose nearest street had low traffic flows to have made two or more medical visits for asthma during the year than to have made only one visit. The results suggest that exposure to motor vehicle exhaust may aggravate symptoms among those diagnosed with asthma.

A GIS developed to model magnetic fields from power lines near households found a significant association with childhood leukemia in Los Angeles County (8). In an earlier study, magnetic field measurements taken over 24 h in bedrooms of 288 homes were fitted by nonlinear regression to a function of wire configuration attributes of power lines (9). Case-control data on childhood leukemia were reanalyzed to assess the associations between the measured magnetic fields and the magnetic fields predicted based on the wire configuration attributes of power lines (69). Childhood leukemia was not associated with the fields measured over 24 h. However, risks were significant for magnetic fields predicted from wire configuration attributes above 1.25 milligauss. A significant dose-response effect was also noted. The GIS analysis of exposure enhanced the analysis in several ways. Because 24-h electromagnetic field measurements are strongly affected by short-term fluctuations, they may not yield as reliable a measure of exposure as the measure developed by GIS modeling. The GIS approach made it possible to enlarge the size of the study to include more subjects and residences because it did not entail obtaining field measurements at hundreds of homes. The GIS could also be used to model exposure retrospectively provided data on wire code configuration of power lines and locations of residences are available.

Critics of these approaches argue that they do not adequately address confounding factors. GIS-based research is playing an important role in addressing the analysis of confounding factors. Proximity to high traffic and socioeconomic characteristics of neighborhoods, for example, have been suggested as confounding factors in the study of risk relationships between proximity to electromagnetic fields and childhood leukemia. In order for these to confound EMF effects, these factors would have to have an independent effect on disease risk. A GIS was used to examine the relationship between these suggested confounding factors and childhood leukemia in San Diego County (58). Ninety cases of childhood leukemia diagnosed in children under 5 between 1988 and 1994 who were born in the county were matched by gender and date of birth to 349 children also born in the county and not known to have cancer. No significant differences were observed for neighborhood median family income in the neighborhood of the birth residence. None of a variety of measures of traffic was associated with cancer.

Some GIS applications have not only linked hazards, exposure, and outcomes, but have taken the final step toward intervention to address health problems. A study conducted in Jefferson County, Kentucky, used a GIS to map blood lead concentrations observed in a cohort of children born in 1995 and screened from 1996 through 1997 and among children less than 7 who had been screened from 1994 through 1998 (57). Based on the 1994 through 1998 data, 79 homes had housed 35% of the 524 children with lead poisoning. As a result of the analysis, these housing units were made a priority for lead hazard remediation. The study also revealed that only about one half of the children who lived in zones designated for universal screening had been screened.

GIS, ENVIRONMENTAL MONITORING, AND PUBLIC HEALTH SURVEILLANCE

GIS applications for the study of disease require spatially referenced data on the sources and distributions of causative agents, the geographical distributions of populations at risk by age, sex, and race/ethnicity, and the geographical distributions of health outcomes. Most of these data layers will be referenced against foundation data layers produced at the federal, state, and local levels like the Census TIGER/Line files, U.S. Geological Survey digital line graph data, and property parcel databases. For certain kinds of agents, the areas where agents are present may be modeled by implementing fate and transport models within a GIS or by modeling climate and habitat controls on the distributions of biological agents. In some cases, measurements taken directly in the field will be georeferenced using GPS and data will be projected and integrated with other data layers in a GIS.

Fortunately for public health analysts in the United States, most of the foundation data layers are publicly available at a relatively low cost. There are, however, problems with the positional and attribute accuracy of these databases. For example, in rapidly growing regions, new streets and subdivisions may not be featured. In addition, the scale of some databases may not be appropriate for a particular study.

The research applications discussed in this review suggest that modeling of the sources and distributions of disease agents is becoming more sophisticated, particularly with respect to chemical contaminants and disease vectors. Spatially referenced databases like the Toxics Release Inventory and other inventories maintained at the state level and satellite images have made these modeling efforts possible. These databases, too, are relatively accessible to the general public. Nevertheless, many of the studies discussed involved substantial supplemental data collection efforts to document conditions in the particular time and place of the study.

Population data are available through the U.S. Census and these data are increasingly distributed over the Internet. To date, complete counts by age and sex have been available only every ten years and annual estimates made only at the county level for age and sex. The Census Bureau is testing new annual sampling and data distribution methods through the American Community Survey program to provide more timely data (72).

Of the spatially referenced data that might be incorporated into a GIS application on disease, health outcome data are the most difficult to obtain. Perhaps for this reason, many GIS applications on disease do not include outcome data. By their nature, health outcome data arise from observations of events made at the local level associated with direct contacts between medical care providers and patients, from vital records, from laboratory tests, and so on and describe the health status of an individual at a particular point in time. These individual records can often be georeferenced to a range of geographic areas such as blocks, tracts, county subdivisions, and other geographic units within the Census hierarchy (70). Digital databases of individual health records or extracts from these databases are the raw material for GIS applications that analyze health outcomes. As with Census responses, individual health records are not publicly available. Some Census data centers and some health agencies, however, allow access to individual health records but only to selected researchers.

The growing use of administrative data on health conditions has led a number of researchers to analyze data by ZIP code area because ZIP codes are frequently the only area identifier available in the record. A number of problems arise in the use of ZIP codes (40). First, ZIP codes are a set of mail distribution points designed to support the activities of the postal service. As a result, they are not stable over time. Second, it is difficult to match ZIP codes to census units for which population data are available. The Census has created ZIP Code Tabulation Areas (73) to address this problem.

The development of disease surveillance systems has emphasized data collection rather than data distribution. When data are reported, most information distributed from surveillance databases is reported for predetermined thematic, temporal, and geographical categories. GIS analysts of disease do not necessarily need access to individual health outcome records, but they do need to be able to obtain databases derived from individual records selected for age, sex, race/ethnicity, and aggregated to user-defined time periods and meaningful geographical areas. The user-defined counts by area can be combined with population data to create rates, if needed. Agencies that maintain these databases may be unwilling, or, in the case of many state agencies, unable to perform detailed queries to satisfy requests for information because of staff shortages.

Online database querying and interactive mapping systems are being developed. Some interesting examples at the federal level include the WISQARS injury statistics query and reporting system (51) and the National Center for Injury Prevention and Control's Injury Maps site (50). The National Cancer Institute also maintains the Cancer Mortality Maps & Graphs site that allows users to map rates and download geographic boundary data (52). The querying capability of the WISQARS system comes closest to allowing users to obtain counts in addition to rates for user-defined characteristics of individuals and their injuries. However, these counts can only be obtained for states. Furthermore, the WISQARS system is not integrated with the Injury Maps site. Such an integration would enable users to select records of interest and then report them in either tabular or map format. The National Cancer Institute site requires particular web browsers and a variety of plug-ins that not all users may have.

The greatest drawback to these sites, however, is the level of geographic aggregation of the data. Developed at the federal level, these sites distribute data for states, state economic areas, or counties. For most GIS applications, these spatial units are not relevant to the geographical processes that shape disease distributions. Settlement geography and land-use patterns are basically a function of state and local government in the United States. As the Census hierarchy of places and Federal Information Processing Standard (FIPS) codes for geographic areas reveal, spatial units vary widely and function differently from state to state and region to region. For example, the town as a unit of local government and county subdivision is an important unit of analysis in New England states but does not exist in other parts of the country. Health care delivery systems, public drinking water systems, and other systems of interest in the study of disease are regulated at the local and state as well as the federal level and, like settlement geography, also vary substantially from place to place. For too many decades, agencies distributing health data have failed to address these important underlying geographical realities.

It is an important challenge to geographic information science to demonstrate how distribution of data for meaningful geographic units can be accomplished. One possible approach is the development of server-side online querying and mapping systems. These systems would permit users to query abstracts of surveillance databases containing individual records to count records with user-defined attributes and to report counts for user-selected geographical units like census tracts or towns within a user-selected geographical domain such as one or more states, local health districts, or public water supply system service areas. Users could then choose to report counts of selected records for the geographical units of interest in the form of a table, a downloadable file, or a map. These systems can be implemented using a full database approach that does not require specialized GIS software or plug-ins. The agency maintaining the database would have to code the records to the various geographical units and code the geographical units to the various geographical domains of interest.

Unfortunately, recent projects and proposals to develop new surveillance systems do not adequately reflect the power of GIS or the importance of a spatial perspective on disease. A diagram of the NEDSS Base System in a document describing the National Electronic Disease Surveillance System now under development by the Centers for Disease Control and Prevention shows GIS running on an application server but does not describe how the spatially referenced data will be collected nor how it will be distributed (16). The analysis, visualization, and reporting functions in Release 1 will apparently provide only basic reporting capabilities (17), probably tabular. A recent proposal to reorganize cancer surveillance in the United States does not mention geographic information systems technology (68). Instead, it calls for the dismantling of state-run cancer registries, even though states pioneered the development of many tumor registries. The proposed alternative focuses on population groups rather than places, limiting the locations for which cancer data will be collected. This would severely limit the study of environmental and place factors associated with cancer and the ability of state and local public health agencies and other researchers to investigate cancer in their own communities.

Two major barriers to realizing the great promise of GIS in the study of disease emerged from this article. First, there is a need for better and on-going environmental monitoring. This includes basic science to design effective environmental sampling and monitoring systems for chemical and biological contaminants. It also includes basic science on the spatial processes affecting the geographical distributions of agents, vectors, hosts, and reservoir populations. There must also be ways of communicating this information to analysts who are designing public health applications of GIS. Second, there is a need for disease surveillance systems that are focused on distributing information for meaningful spatial aggregates that meets the needs of the larger research community and the general public.

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LITERATURE CITED

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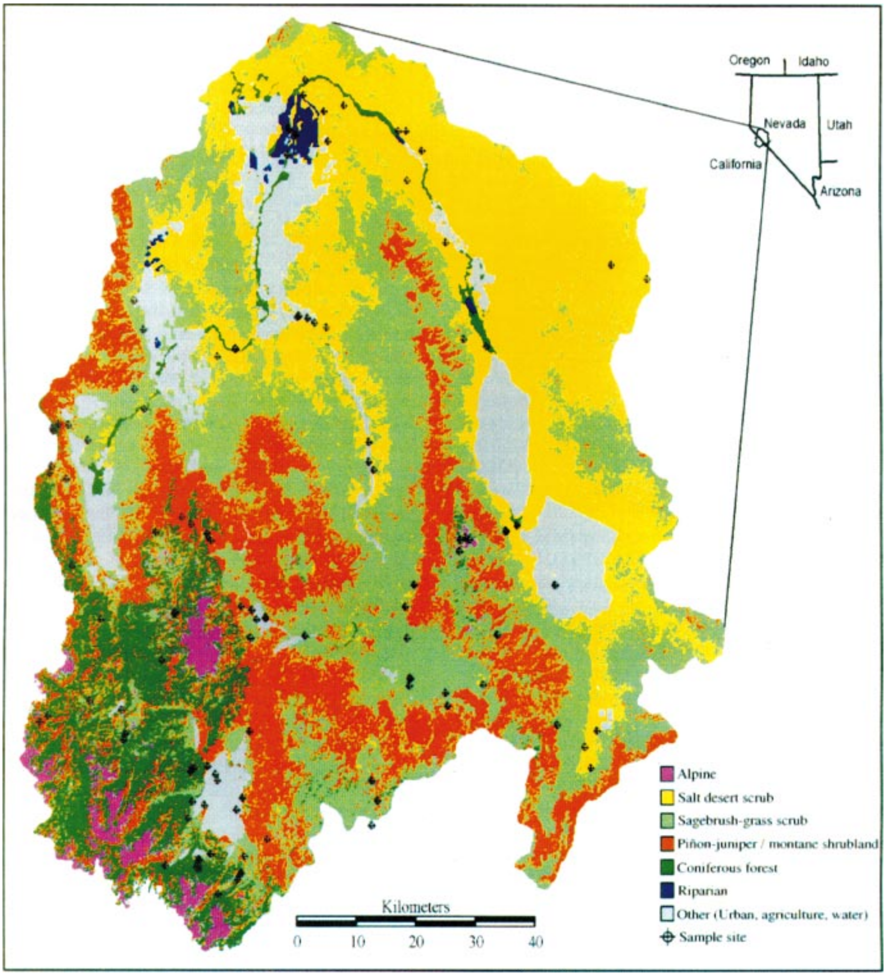

Figure 2 Location of Walker River Basin and its eight major vegetation types generated from Landsat Thematic Mapper images and digital elevation data. Reprinted from *Emerging Infectious Diseases*, Vol. 6, No. 3, 2000, pp. 248–58, Boone et al., "Remote sensing and geographic information systems: charting Sin Nombre virus infections in deer mice," (6).

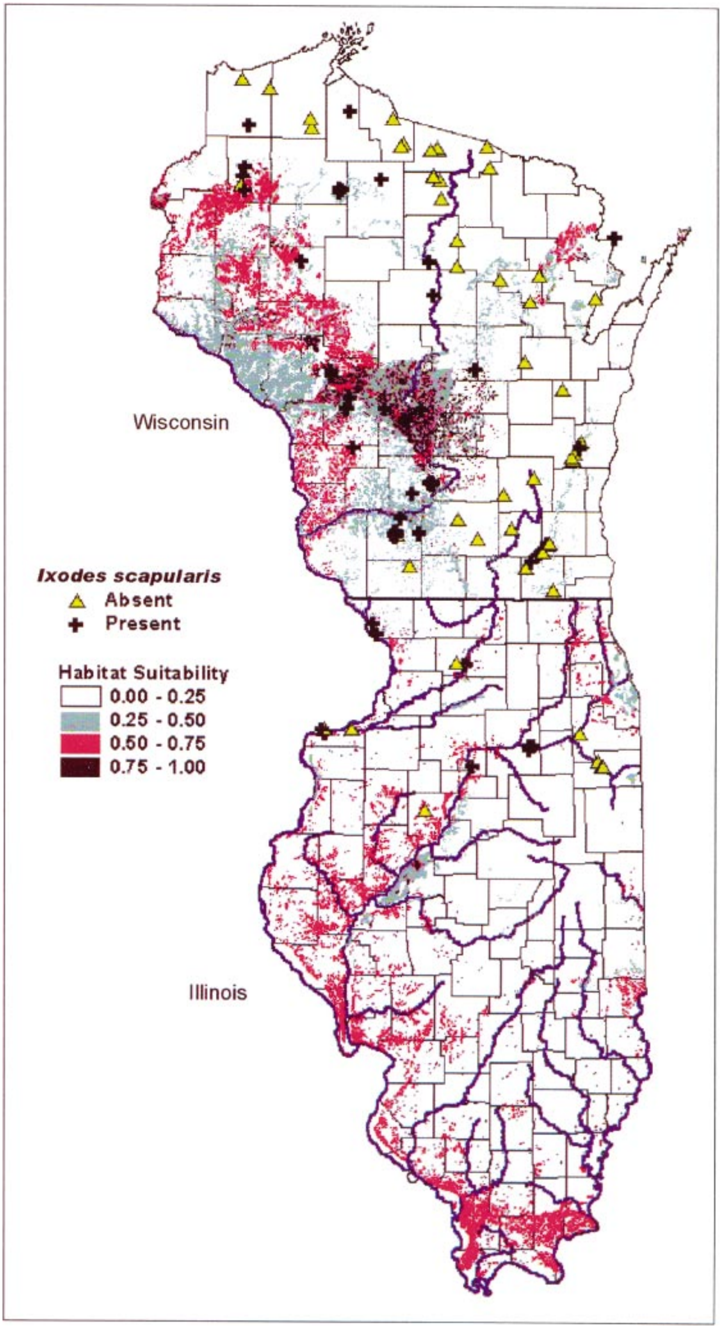

Figure 3 Predictive risk map of habitat suitability for *Ixodes scapularis* in Wisconsin and Illinois. Reprinted from *Emerging Infectious Diseases*, Vol. 8, No. 3, 2002, pp. 289–97, Guerra et al., "Predicting the risk of Lyme disease: habitat suitability for *Ixodes scapularis* in the north central United States," (30).

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