CHAPTER 12

Geographic Information Techniques in Research

Learning Objectives:

- What is geographic information, what forms does it come in, and what are some ways it is used in geographic research?
- What are some important considerations when analyzing, mapping, and interpreting geographic information?
- What is spatially referenced remotely sensed imagery, and what are some ways it is used in geographic research?
- What are the major analytic capabilities of GISs?

The increased availability and sophistication of computers in the last several decades has enabled the development of geographic information systems (GISs). GISs have the capability of storing, manipulating, analyzing, and displaying **geographic information**. Geographic information is any information that is spatially referenced to the surface of the earth. Historically, geographic information was limited to verbal descriptions and increasingly sophisticated maps. Today, geographic information is stored digitally in simple and complex data structures on computer-readable media. The abstraction of spatial reality to these digital data structures both limits and extends our understanding of geographic processes and phenomena. Remotely sensed imagery from satellites, aerial photographs, and other sources provides a significant subset of geographic information used by geographers, both human and physical. This chapter overviews (1) geographic information and spatially referenced remotely sensed imagery, (2) the nature and capabilities of GISs, and (3) some of the spatial and nonspatial types of analysis that are significantly enabled by GISs.

Geographic Information

Fundamentally common to all geographic information is its spatial reference to the surface of the earth, as conceived and measured. Human conception of the earth has evolved from a large if not infinite flat plane to a sphere to an **oblate spheroid** to the **geoid**. As we mentioned in Chapter 1 and discussed further in Chapter 4, geodesy is the science of measuring the size and shape of the earth, and the distribution of physical and human features on its surface. Geographic information includes geodesic information but is more general in that it includes any information with a spatial reference to the sphere, oblate spheroid, or geoid. However, characterizing the nature of geographic information gets somewhat complex when we consider what is being represented, how it is measured (including uncertainty in those measurements), the spatial and temporal resolution at which it varies and is measured, and the data models and structures used to represent the information. These characteristics are interrelated in ways both subtle and not so subtle. They are very important because they influence how you can or should display, manipulate, and identify patterns in data. The nature of geographic information is an essential component of research methods and must be carefully considered before and during geographic inquiry. Furthermore, considerations about how geographic information has been handled constitute an important basis for critiquing the research of others.

For example, consider the four following kinds of geographic information: (1) The location and elevation of all mountain peaks in Colorado above 14,000 feet, (2) a 1 km^2 resolution grid (or raster) of the population density of the nation of India, (3) those areas of the conterminous United States where threat of exposure to the West Nile virus is high, and (4) the flight paths of all United Airlines flights on June 27, 1998. Our four examples might typically be represented, respectively, as points with elevation attributes; a grid of cells, each containing a population count; a polygon **coverage** (layer), each polygon scored for a threat level; and a set of lines (we discuss data models and structures below). All of these representations inherently contain some degree of spatial, temporal, and thematic error that must be considered, but the types and amounts of error associated with each vary dramatically. Global Positioning Systems (GPSs), discussed below, allow us fairly accurately and precisely to locate the 14,000-foot peaks in Colorado, whereas the population density of India changes daily in space and grows with time. Risk associated with the West Nile virus is not completely understood; therefore, maps of that risk are "fuzzy" at best or completely wrong. The United Airlines flights actually did take place along very specific routes; however, the accuracy of the instrumentation we use to map them is limited.

Although the comprehension of geographic information may seem daunting, you may find it somewhat comforting that the "children's" placemats that many restaurants give to kids of all ages often contain puzzles and activities that use the basic models of geographic information. A "connect the dots" puzzle on those place mats uses numbered points that can be used to create points, lines, and polygons. Even the "word search" puzzle is a raster representation of letters. Needless to say, commonly used geographic information is substantially more sophisticated but nonetheless comprehensible with a little effort. The following are important characteristics to consider when creating, analyzing, or mapping geographic information:

1. ***What is the nature of the phenomenon or entity being represented?*** As individuals and members of cultural subgroups, we conceptualize geographic phenomena (features and events) in terms of **conceptual models**. These are simplified mental or intellectual representations of phenomena in the world. The most fundamental conceptual distinction when representing geographic phenomena is that between **fields** and **objects**. This is the distinction we touched on in Chapters 2 and 8 between continuous and discrete reality. A clear example of a field is temperature, a continuously varying phenomenon that exists everywhere in space. Other examples include humidity, elevation above sea level, and barometric pressure. In contrast, a clear example of geographic objects would be fire hydrants. Fire hydrants are discrete entities, with fairly clear and precise boundaries, that exist in some places and not in others. Examples of geographic features often best suited to object representation include islands, water bodies, buildings, and streets.

Phenomena in human geography are very frequently modeled as objects, whereas those in physical geography are often modeled as fields. However, some geographic phenomena do not lend themselves obviously to object or field conceptualization. Often, the issues of object versus field are related to the spatial and temporal resolution of measurement—matters of scale. Consider the geographic phenomenon of population density. Population density is typically a number attributed to a polygonal area or a pixel: the number of people in that area divided by its areal extent. In actuality, however, population density is a temporally varying number of discrete humans in a given subset of continuous space. Imagine yourself chatting with a friend at a party—does the space between you and your friend have the population density of the room or the city you are in, or is it simply zero? For some applications, it might be reasonable to conceive of population density as a field; an example is a regional study of human impact on the environment. In other applications, an object-based representation would be preferred; an example is urban warfare. Similar issues are encountered in physical geography when studying vegetation—do you look at the forest, the trees, or a field of vegetation density? In any case, you should give careful consideration to the nature of the geographic phenomena you are attempting to represent in maps or data, and how those representations will be used and compared with other geographic information relevant to your particular inquiry.

2. ***Spatial scale or resolution of measurements.*** Questions about how information is measured are related to the previous question regarding the nature of the phenomena being studied. That includes the relationship of analysis scale to phenomenon scale (see Chapter 2). As we discussed in Chapter 9, geographic information is measured and analyzed at various spatial scales and is frequently aggregated from a larger set of measurements into a smaller set of measurements applied to the inquiry at hand. Terms such as **resolution** or **granularity** are often used as synonyms for analysis scale, especially when the information is in the form of digital

representations by means of a regular grid of small cells in a satellite image (**rasters**) or on a computer screen (**pixels**). Analysis scale would then refer to the area of earth surface represented by a single cell.

In Chapter 9, we reviewed many of the difficulties and ambiguities caused by the uncertain relation between analysis scale and phenomenon scale. However, scale difficulties are not limited just to issues of the proper size or resolution of measurement units, because geographers are often interested in linkages that occur across varying scales, such as "local to global" or "global to local"; these linkages are expressions of the hierarchy of scales, introduced in Chapter 2. Linkages of this nature can be independent of, or confound, questions associated with the spatial and temporal scale of measurement. For example, identifying a large-scale El Niño pattern (that is, over a large area) in the eastern Pacific Ocean during the spring may tell us a great deal about small-scale (over a small area) rainfall in many parts of Africa during the following summer. This is an example of identifying a potentially useful global-to-local linkage. In order to study this, you would probably want historical information about both the El Niño in the Eastern Pacific and the rainfall in Africa. The El Niño data could range from nominal or ordinal descriptions of the El Niño for several decades (for example, 1979 El Niño "yes," 1980 El Niño "no") to complex time-series satellite images of sea surface temperature. The African rainfall data could range from aggregate measures based on farmers' reports ("1981 was a good rainfall year around here") to a whole network of rain-gauge data from hundreds of stations in locations around the continent.

3. ***Temporal scale or resolution of measurements.*** All geographic phenomena vary as a function of time; no earth phenomena even existed a few billion years ago. Consequently, one must consider the rate at which geographic phenomena change. Clearly the location and elevation of Mt. Everest, the flow of the Mississippi river, the population of Yankee stadium, and the proportion of likely voters favoring presidential candidate Bob vary on different timescales. The temporal scale of measurement of geographic information is consequently another important aspect of research methods. Annual rainfall information is likely inadequate for understanding specific meteorological events like storms or hurricanes. Daily traffic counts for roads and highways in a street network may be useless for understanding traffic patterns that vary on a minute-by-minute or hourly basis. GISs still have room to improve with respect to handling temporal information. The development of dynamic models that describe urban growth patterns, for instance, presently constitutes an important current research focus in geography. One fundamental question associated with this kind of work concerns what temporal resolution is required for the geographic information represented in the models. The development of dynamic models describing two- and three-dimensional geographic processes will be an increasingly vibrant area of research in the future.

Temporal resolution is particularly interesting in the context of satellite remote sensing. The temporal density of remotely sensed imagery is large, formidable, and growing. Satellites are collecting a great deal of imagery as you read this sentence. However, most applications in geography do not require extremely fine-grained temporal resolution. Meteorologists may require visible, infrared, and radar information at sub-hourly temporal resolution; urban planners might require imagery at monthly or annual resolution; and transportation planners may not need any time-series information at all for some applications. Again, the temporal resolution of imagery used should meet the requirements of your geographic inquiry. Sometimes researchers have to delve into archives of aerial photographs to get information from the past that predate the collection of satellite imagery.

4. ***Thematic scale and classification of features.*** In Chapter 2, we pointed out that scale was not just relevant to space and time but also to theme. **Themes** are the non-spatial and nontemporal characteristics of human and natural phenomena that geographers measure as variables and store as attributes in information systems. Like space and time, themes can be aggregated or disaggregated to various levels. A biogeographer can study plant subspecies, species, families, or vegetation communities. An economic geographer can study the manufacturing of computer chips, computers, all electronic goods, all high-tech goods, or manufactured goods in general. As with spatial and temporal scale, you need to think about the proper thematic scale at which to study your phenomena of interest.

Research issues involving the thematic content of geographic information go well beyond the question of the proper thematic scale at which to study a problem, however. We claimed in Chapter 1 that nearly all scientists accept a philosophy of realism; they believe the universe actually exists and is not a mere construction of human minds. We also pointed out, however, that the patterned matter and energy that make up reality is organized into meaningful pieces—objects and events—by sentient beings. In fact, this organization, essentially a process of interpretation, is a fundamental mental activity carried out constantly in an informal way by everyone, including scientists. But scientists carry out this interpretation more systematically, with greater concern for the coherency, consistency, and reality correspondence of the ontologies that result. **Ontologies** are systems of concepts or classes of what exists in the world; they reflect the structure of objective reality as well as personal and social acts of cognitive organization.[1]

Geographers must also concern themselves with the nature of geographic reality, recognizing that the tools of their intellectual and empirical efforts are verbal, graphical, and numerical *models* of reality that necessarily depend on categories of

[1]In Chapter 1, we defined the study of epistemology as how scientists (and others) can know what they know. As traditionally defined in philosophy, and in Chapter 1, ontology deals with the question of the objective nature of that which actually exists. Ontology and epistemology together make up the traditional domain of metaphysics. We are using the concept of ontologies in a broader sense that has become quite popular in the information sciences, including geographic information science, since the 1980s. This broad sense more or less combines ontology with epistemology in recognizing that human concepts of reality, whether in human minds, cultures, or information systems, depend as much on human conceptualization as on the nature of reality. We'll leave the question of whether we can ever know the nature of reality independently of human conceptualization for you to ponder during your next midnight philosophy session.

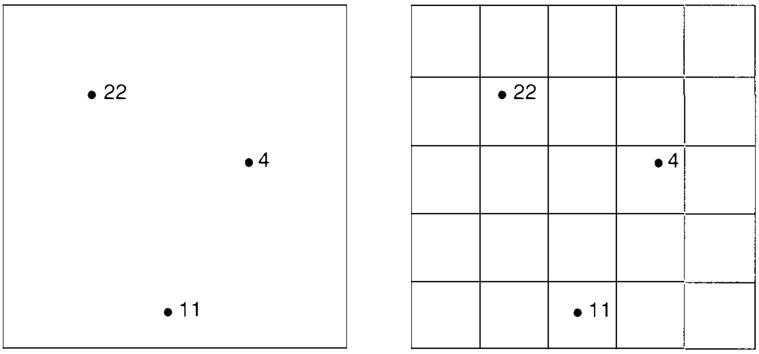
earth and human structures and processes. Cities, mountains, rivers, and industries cannot be understood simply as elements of reality sitting out in the world for geographers to objectively assess. They are also products of what geographers choose to focus on in the world and how geographers organize their perceptions into units of reality. This is true when geographers study their phenomena directly via field and lab observations, and it is true when they study their phenomena indirectly via maps and remotely sensed imagery. Most people can readily see the ambiguity of trying to classify all forms of agricultural activity as "intensive" versus "extensive," or of trying to classify vegetated land cover as "grassland" versus "broadleaf forest" versus "needle leaf forests" versus "mixed forest"—surely there is grass to be found in all four land cover classes. But it is even ambiguous to define "lake" clearly enough so that the exact number of them in Minnesota can be counted accurately. That's right, no one knows *exactly* how many lakes there are in the "Land of 10,000 Lakes," except by making some partially arbitrary decisions about what constitutes a single lake.

The nature of geographic ontologies has great implications for the potential of different people, cultures, disciplines, and information systems to "communicate" effectively with one another about geographic phenomena. In the information sciences, this is known as the problem of **interoperability**. In addition to geography and computer science, linguistics, cultural anthropology, cognitive category theory, and artificial intelligence are all important to the study of the interoperability of geographic information systems, a cutting-edge area of research on geographic information.

Data Models and Data Structures

Our conceptual models of geographic phenomena are represented in simplified form in the computer in terms of a **data model**—a simplified computer representation of the spatial, temporal, and thematic attributes of geographic information. We represent most geographic information in terms of either the **vector** or **raster data models**.[2] The vector model consists of geometric objects formed by vector connections among node points in the data space, and includes features modeled as **points**, **lines**, or **polygons**, which are zero-, one-, or two-dimensional features (three-dimensional **volumes** are possible as well). Spatial information in a vector model is expressed in terms of the coordinates assigned to the vertex points and any geometric inferences that can be made from those coordinates. In contrast, the raster model consists of a regular grid of small cells, usually square, that **tessellate** the planar surface like a big checkerboard with values in each cell. A raster does not represent coherent objects as such. Spatial information in a raster model is expressed in terms of the coordinates assigned to the raster cells and any geometric inferences that can be made from those coordinates. The vector-raster distinction is often described as the data-model equivalent of the conceptual distinction

[2]There are other, less common geographic data models, such as "triangulated irregular networks" (TINs) and various hybrid models.



Vector Data Model
three points in space
with numerical attributes

Raster Data Model
with coordinate
system superimposed

Pt. ID	X	Y	Value
1	1.5	3.5	22
2	3.5	2.5	4
3	2.5	0.5	11

Vector Data Structure

0	0	0	0	0
0	22	0	0	0
0	0	0	4	0
0	0	0	0	0
0	0	11	0	0

Raster Data Structure

Figure 12.1 Data models and data structures.

between objects and fields, although this equivalence is inexact at least insofar as rasters digitally represent fields as collection of small grid objects, not as truly continuous entities.

In turn, our data models of conceptual phenomena are digitally expressed in the computer in terms of a **data structure**.[3] Consider a simple data set of thermometers measuring temperature at three locations in space. The data model is simply three points in space with temperature measurements attributed to them (Figure 12.1). A **coordinate system** could be imposed on this data model to facilitate describing the relative locations of the points. The data structure associated with this data model will be significantly different depending on which data model is chosen to represent the geographic information. In the case of a vector representation, the data structure would simply be three lines of numbers in addition to an ID code (*X-coordinate, Y-coordinate,* and *Temperature Value*), perhaps separated by commas, easily stored as an ASCII text file. In the case of a raster representation, the data could be stored as five rows of five numbers or *n* rows of *n*

[3]Our use of the term "data structure" conflates a distinction that is sometimes made between low-level data structures that express the fundamental machine code used to represent information digitally and "data formats" that connect low-level structures to high-level data models.

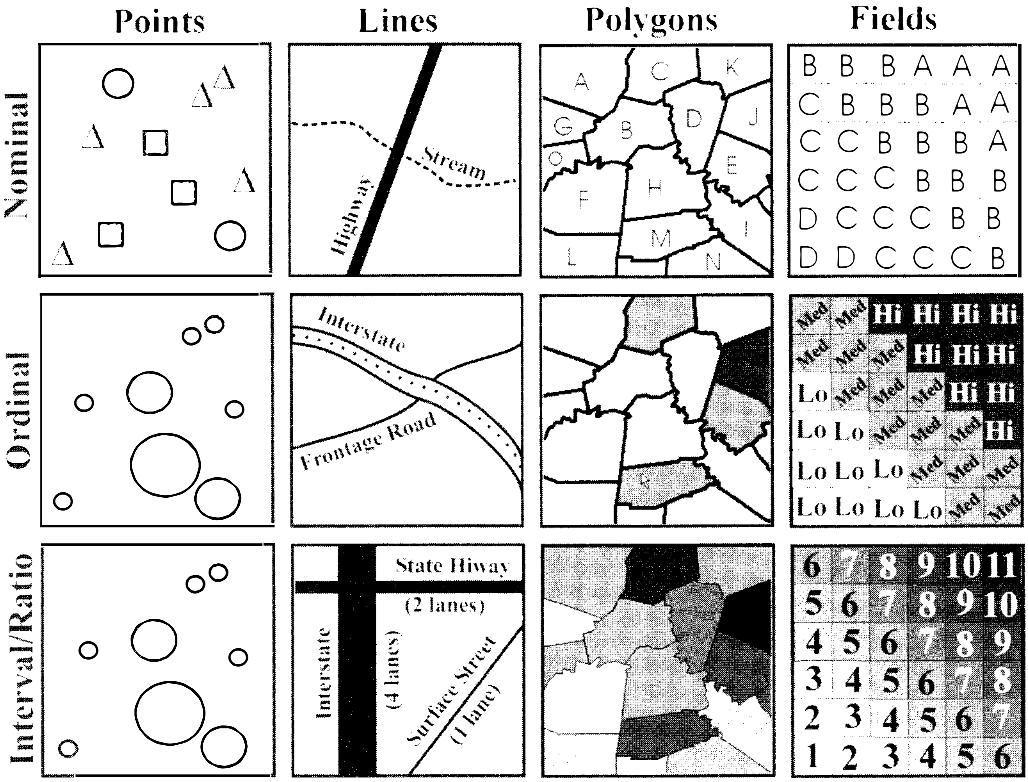


Figure 12.2 Schematic representation of entity-attribute spatial data types (adapted from O'Sullivan & Unwin, 2003)

numbers, depending on the spatial resolution of pixels or grid cells considered appropriate. Note that in the raster data structure example, zeroes represent "No Feature Present."

It is important to consider data models and structures because they influence how data can be processed and displayed and how certain analyses can be performed, as well as how errors in those analyses might propagate. Figure 12.2 depicts 12 different spatial data types that result from cross-tabulating measurement level (nominal, ordinal, interval/ratio) against the three major vector data models (points, lines, and polygons) and the raster data model (fields).[1] These 12 different data types are best displayed graphically in different ways, propagate error differently, and lend themselves to different kinds of spatial analysis. We often have choices as to how we want to represent geographic information; the data model we choose is an important characteristic of geographic information that we must carefully consider when doing research.

[1]Based on O'Sullivan & Unwin (2003).

Remotely Sensed Geographic Information

We have noted in Chapters 3 and 4 that geographers frequently collect data by observing physical traces of human and natural activity on the earth's surface. This is commonly done from above by image recording devices carried by airplanes or satellites. Although information derived from satellite images, aerial photographs, and other imagery is simply a subset of geographic information in general, such **remotely sensed geographic information** does warrant some special consideration. Remotely sensed images can record solar radiation reflected off the (near) earth surface, radiation emitted from natural and human features, and radiation bounced off near-earth surfaces that were emitted originally from the sensors themselves (for example, Lidar and radar); the first two are known as **passive sensing**, and the third is known as **active sensing**. Remotely sensed images of the earth surface were historically derived from optical photographs taken from airborne vehicles such as planes or balloons. Today the majority of remotely sensed imagery comes from satellites in outer space.

Aerial photographs were originally black-and-white images taken in the visible range of the electromagnetic spectrum. This naturally evolved into color photographs, which provide more spectral information—separate information from the red, green, and blue portions of the spectrum. Later, color-infrared film was developed that provided information from the infrared part of the electromagnetic spectrum, a profound development for assessing the health and water content of vegetation. The development of more sophisticated sensors has expanded the **spectral resolution** of remotely sensed imagery, an aspect of thematic scale, to a dizzying extent. There are now satellites and airborne sensors producing remotely sensed images of the earth in the radar, microwave, visible, near-infrared, thermal infrared, and ultraviolet parts of the electromagnetic spectrum. Detailed descriptions of the potentials of these different types of imagery are beyond the scope of this book, but the interested reader can look at the books we list in the bibliography, or better yet, take a course in remote sensing.

Multispectral remotely sensed imagery in some sense has the "layer-like" characteristics of a set of vector data layers (for example, road layer, soils layer, county layer) in which each spectral band is a layer. These data sets sometimes have hundreds of spectral bands and are referred to as **data cubes**. The size of these data cubes can become overwhelming. Imagine a 1,000 by 1,000 pixel image, about the size of a typical computer monitor, that has 256 separate layers representing narrow slices of the electromagnetic spectrum; that is, each pixel of the image has 256 **data numbers** or values associated with it. Analysis of a time series of this kind of data set actually starts to make computers work hard. The data volume of remotely sensed imagery can become staggering, really exceeding the comprehension capability of the human mind. What's more, many of the data are partially redundant; for example, several spectral bands sensed from the same area of ground surface will often be strongly intercorrelated and thus represent less information than they appear to. Consequently, the analytic techniques of remote sensing typically include methods to reduce the spectral, spatial, and/or temporal resolution of the imagery in order to reduce this redundancy and make the information interpretable by humans. The amount and type of resolution reduction applied to an image is preferably determined by the needs of the user.

Remotely sensed imagery comes in a large range of spatial resolutions. The spatial resolution of remotely sensed imagery must be appropriate to the research questions it is being used to investigate, but choosing the spatial resolution of imagery appropriate for your particular research can be challenging. Aerial photographs can be obtained in which the spatial resolution is measured in inches, whereas radar images can have spatial resolution measured in kilometers. *IKONOS* imagery provided by the Space Imaging Corporation is provided at 1-meter resolution. Despite the dramatic improvements in computational power over the last decade it would be very difficult to meaningfully display a composite *IKONOS* image covering, for instance, the state of Alabama. Global image products with spatial resolution less than 1 kilometer are pushing the computational capabilities of computer systems to some degree. In general, it is fairly easy to reduce the spatial resolution of imagery via aggregation to larger pixels; however, this is not always a good approach. In addition, it should be noted that finer-resolution imagery is not always the best means of getting "better" information. For example, consider an attempt to map and identify "exurban" areas of the United States. Exurban areas are residential developments outside of the traditional suburban boundaries of 20th- and 21st-century urbanized areas. They are rural, wilderness, and small town areas that contain residents engaged in traditional urban economic activities by commuting or telecommuting to urban workplaces. To identify these areas, a 1-kilometer-resolution nighttime image proves to be more useful than a 30-meter-resolution image derived from *Landsat* imagery (Figure 12.3). Lights from exurban development are captured in the nighttime image, although the buildings associated with those lights are lost in the forest of the 30-meter *Landsat* image. Although the fine-resolution *IKONOS* imagery captures some of the exurban development, it would be prohibitively expensive both financially and computationally to do this analysis across the United States with 1-meter imagery. Figure 12.3 presents several spatial resolutions of remotely sensed imagery that show both the benefits and drawbacks of finer spatial resolution.

Likewise, it is important to know the temporal resolution of imagery data. Production of the aforementioned nighttime imagery by the Defense Meteorological Satellite Program's Operational Linescan System (DMSP OLS) provides a good example of data reduction that utilizes temporal resolution to improve the quality of the data product. Global products of the DMSP OLS imagery are available at 1-km resolution for city lights, gas flares, lantern fishing, lightning, and forest fires. None of these products could be produced from a single night's observations because of clouds and the fact that different kinds of light are confounded with one another. The city lights product, one of the most popular of these data products, would not be possible without manipulation of the temporal characteristics of the DMSP OLS imagery. The city lights data product is produced from hundreds of orbits of imagery that occur throughout the year. The DMSP OLS system has a thermal band that allows for the screening of cloud impacted imagery;

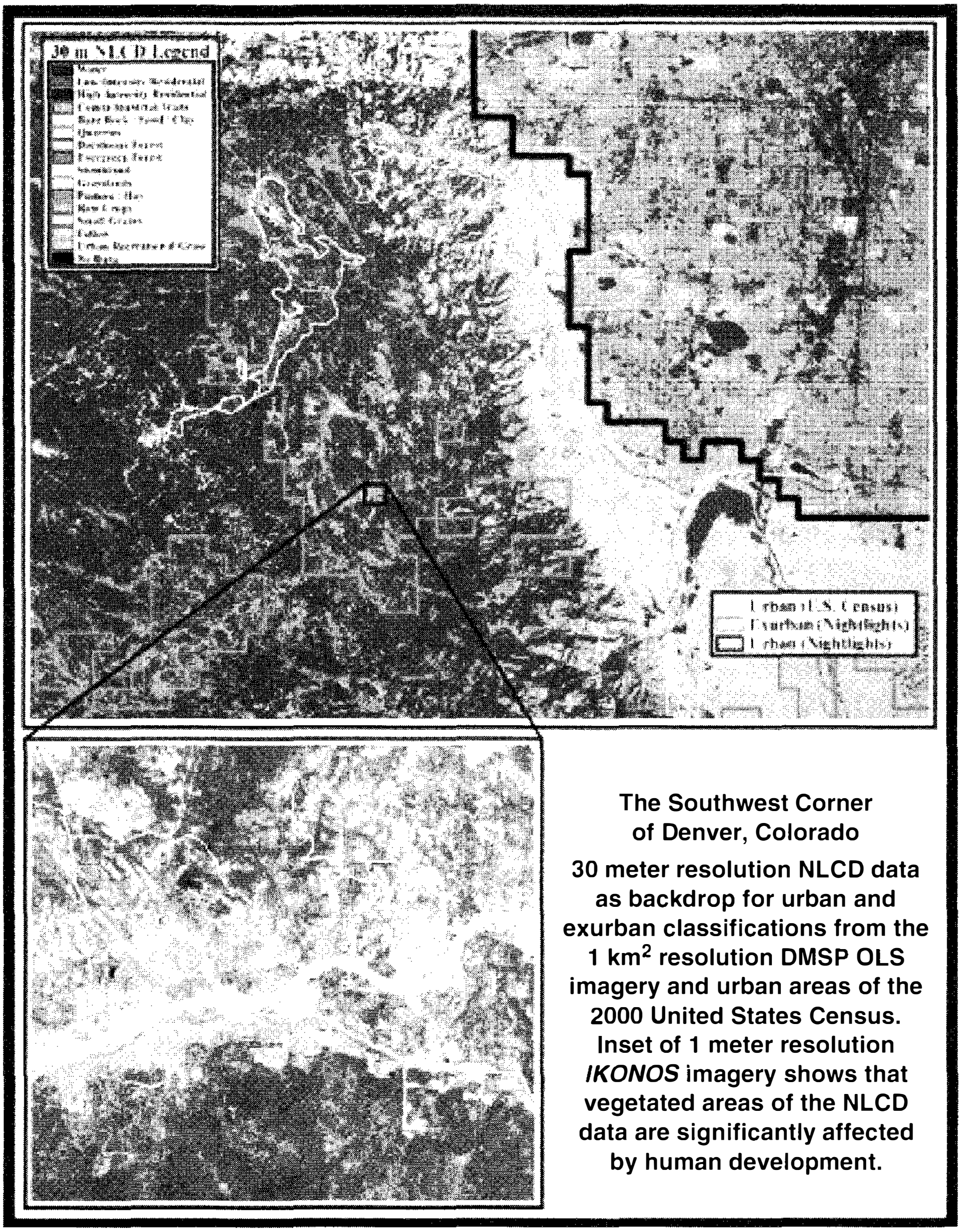


Figure 12.3 Identifying exurbia in remotely sensed imagery, as a function of spatial resolution.

geo-location of the imagery allows for discriminating where the light sources come from—land or ocean, Middle East or Texas, and so on. City lights are generally nonephemeral and occur every night in a given pixel; fires and lightning are ephemeral and can be distinguished on the basis of their temporal behavior and spatial context. Thus, the city lights nighttime image data product is produced at an annual temporal resolution and enhanced in accuracy by collapsing the daily measurements made by the satellite from which it is derived.

Let's consider an example of how imagery resolution reduction works in the context of spectral resolution and thematic classification. *Landsat* imagery is provided at 30-meter spatial resolution (pixels contain information about 30 m by 30 m squares of earth surface) with seven bands of spectral information: ultraviolet, blue, green, red, near-infrared, mid-infrared, and thermal infrared. Typically, when a *Landsat* image is displayed on a computer, the user chooses to display three of the seven bands to make unique color combinations for each pixel. However, remote-sensing GIS software (for example, ENVI or Erdas Imagine) can apply mathematical techniques that use all the spectral information for each pixel to classify them into a number of unique categories. A typical application of these methods would be to classify a *Landsat* image into land use/land cover types, such as "deciduous forest," "grassland," "water," "urban," and so on. The classified image would then become a "single layer" image in which the pixel values take on nominal land use/land cover values (for example, 1 = water, 2 = urban, and so on). Classification of remotely sensed imagery is in essence a data reduction technique in which the spectral resolution of the image is reduced to increase its usefulness and interpretability.

Geographic Information Systems

Geographic information systems (**GISs**) consist of the hardware and software used to store, query, display, manipulate, and analyze geographic information. It is no exaggeration to describe the contribution of GISs to geography, and several other disciplines and professions, as revolutionary, but it is critical to recognize that the value of a GIS cannot be realized without human capital (including data collectors, analysts, and programmers) and social capital (including institutions and infrastructure). GIS technology began in the 1960s and has developed dramatically since then. Its future potential appears to be nothing short of incredible. In fact, GISs may become the standard for databases of all kinds in the future, when the capability of traditional databases is combined with the benefits of utilizing any spatial content that is part of the information in the databases. This could be considerable, of course, when we remember that so much information is from or about a *place*. Perhaps the abbreviation "GIS" will evolve from meaning geographic information system to meaning *general* information system.[5] In any case, GISs have become fundamental tools for conducting geographic research in many topical domains. In the rest of this chapter, we review the basic functions of GISs and consider their powers and limitations. We begin with a look at using GISs to store geographic information.

[5]Recently, "GIS" has frequently come to be defined as **geographic information science**. Geographic information science is the discipline, or collection of disciplines, that emerged during the 1990s as the scientific study of geographic information, including its representation and use in computers, human minds, and societies. To avoid confusion, geographic information science is often abbreviated as "GISci."

Information Storage

Most GISs can store information that is spatially referenced to an earth coordinate system (for example, latitude-longitude or some map projection), spatially referenced to itself (for example, features in the data are located relative to other features), or aspatial (not spatially referenced at all). Ideally, geographic information is best stored as spatially referenced to the earth surface. This allows one to spatially "cross-reference" it with other **geo-referenced information**. This information can be based on digitized maps, census data, remotely sensed imagery, data collected from observation in the field, surveys, or any other source. Storing information in a geo-referenced manner allows for many kinds of data manipulation, display, and spatial analysis that would otherwise be impossible. Consider the three temperature measurements described in the section above on data models and data structures. If these temperature measurements were stored with geo-referencing, they could be compared to other geo-referenced information such as elevation, population density, or rainfall. If they were stored without geo-referencing, they could be compared only to other information collected using the same "lost in space" coordinate system, and that information may not even have come from the same part of the world. If they were stored without any spatial reference at all (aspatially), then it would be difficult if not impossible to compare them with other geographic information, and simple calculations such as the distance between measurements could not be made.

Geographic information is stored as points, lines, polygons, or fields, and it is linked to associated tables containing one or more numbers, text units, or images. The spatial reference of geographic information manifests itself in many ways. It is now generally accepted that the earth is a somewhat "bumpy" oblate spheroid orbiting the sun. The development of this understanding of the size and shape of the earth co-evolved with the mechanisms we used to map and measure it. Today, one of the most sophisticated and accurate systems for measuring locations on the earth is the **Global Positioning System (GPS)**. The GPS consists of a suite of satellites that communicate via timed radio signals to receivers and base stations on the surface of the earth; the Bibliography contains references that explain this in detail. With a GPS receiver, one can fairly precisely map oneself or any other object onto our beloved bumpy and nearly spherical geoid. Consequently, a GPS receiver is an excellent way to obtain geo-referenced coordinates (typically latitude and longitude) for any entities or phenomena on the surface of the earth, and they are increasingly being used for this purpose.

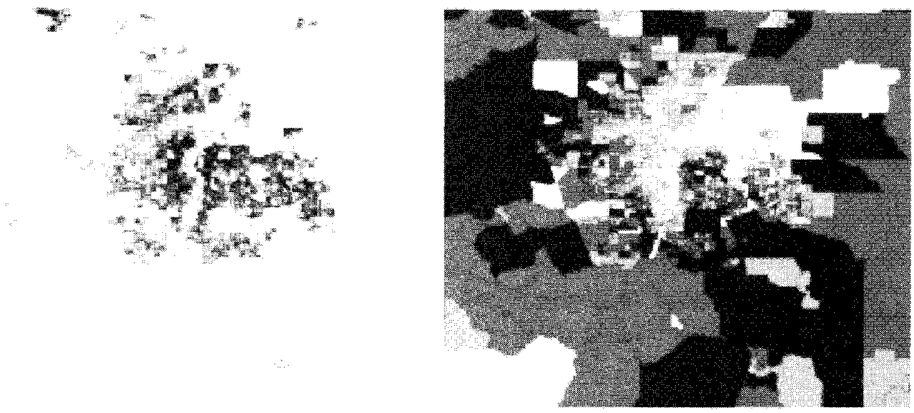
Satellite images and aerial photographs provide information that is also best analyzed when geo-referenced, but such imagery is sometimes obtained without any geo-referencing at all. To geo-reference this "lost in space" imagery, ground control points with known geo-reference are used. Sometimes the imagery comes with complex orbital information about the location of the sensor that produced the image. This can also be used to geo-reference the imagery. However, a great deal of spatial information in geography, particularly human geography, does not use GPS or geo-referenced satellite imagery at all. Census data, economic data, and survey data can all be geo-referenced, although they often are not. Survey data could be geo-referenced according to the home or work address of the survey respondent. This would likely be done using a street network data set and the address matching functionality of a GIS. Economic data such as median household income could be geo-referenced by attributing the data to polygons that delineate the geographic boundaries of the regions from which the data were derived.

Data Query and Display

We pointed out in Chapter 10 that GISs provide powerful opportunities to query and display geographic information that far exceed not only traditional paper displays such as maps, but electronic calculators and other nongeographic computer databases. Displaying geographic information against the background image of its portion of the earth surface gives us many advantages over traditional databases when it comes to understanding data. It can help us identify errors or inconsistencies in the data, unanticipated spatial and temporal patterns, and previously unrecognized relationships that exist among data from diverse sources. These capabilities, when combined with the human ability to perceive spatial patterns, extend GIS functionality beyond that of traditional database systems.

A traditional database stored in a system like Oracle or Microsoft Access is typically a bunch of tables (you can think of them like Excel spreadsheets) that are usually linked together by common "key" columns. The functionality of these databases constitutes a powerful set of tools enabling the exploitation of the information they contain. A simple example of this functionality is the ability to query linked tables of information. Imagine a table that consists of names, social security numbers, and tax returns. Imagine another table that consists of the social security numbers, Visa card numbers, and addresses of people. These data could be queried via a traditional database system to identify the Visa card number of those people whose annual income exceeds $200,000. The same functionality is available with a GIS, but the results of the spatial query could then be mapped simultaneously with the tabular result of the query (in this example the addresses could be address matched and mapped). This operation would be useful to a researcher who wanted to contact people living in particular areas to solicit their participation in a research study.

Our example can be extended to show some of the profound benefits that can result from displaying geographic information with a GIS. Suppose you downloaded census data for the Denver metropolitan area. You load them into a GIS and display the population density of the census block groups of the metro area. Figure 12.4 shows the block groups of the Denver area displayed by both population density and housing value. Even without a legend, most people would be able identify the image on the left as being population density. If you displayed population density and the image looked like the image on the right, you would seriously explore the possibility that your data were corrupted in some way (or that you had not commanded the GIS to display them properly). Your ability to "see" that the left-side image "makes sense" and the right-side image "does not make sense" as a representation of population density could come from your knowledge of one or more of the following: (1) You could have firsthand knowledge of the Denver area; (2) you could know that in general the highest population densities in U.S. cities



Census data (block groups) for the Denver, CO, area mapped according to population density and housing value

Figure 12.4 Seeing spatial patterns in census block groups of Denver, CO

tend to be in the city center, and that population density generally drops off with distance from the city center; or (3) you could know that census tracts try to encompass the same number of people, and that smaller ones are therefore more densely populated. Imagine trying to catch such an error if the output were simply a table of block group numbers and their associated population densities. The ability to display geographic information easily in map form is a profound advantage of GISs over traditional database systems. This ability of GISs to quickly and easily display spatial data begs the researcher to use this functionality for the purpose of quick and easy error checking, and in the process, to do some preliminary exploratory analyses that can help identify errors or inconsistencies in the data, unanticipated spatial and temporal patterns, and unrecognized relationships that exist among diverse data sources. These capabilities, used in tandem with the human ability to perceive spatial patterns, extend GIS functionality far beyond that of traditional database systems.

The profound capability of GISs for data query and display can be further demonstrated with this "over the top" example. Suppose you have a nighttime satellite image of Santa Barbara County, a polygon coverage of the census tracts, a street coverage of the county, and a point coverage of 700 Santa Barbara residents who took a survey on their attitudes about gun control and abortion. If you were courageous, you could use the black-and-white nighttime image as the background, display the population density of the census tracts as a semitransparent overlay in varying shades of red, and display the streets with symbols showing government jurisdiction, width of streets displaying street type (gravel, paved, interstate), and various shades of green showing traffic density. On top of it all, you could display the points with symbols showing survey respondent sex ("M" for male, "F" for female), the size of the symbol showing attitude about gun control, and the color showing attitudes about abortion. This map shows variation on at least eight variables but could be created from the data in a matter of minutes (interpreting this complex map is another story). In addition, a good GIS could virtually instantaneously calculate the correlation between population density and the measured attitudes about gun control, determine whether or not there is a statistical difference between the men and women in their attitudes about abortion, and determine whether or not this sample of survey respondents was likely to be spatially randomly selected from the population of Santa Barbara county. A GIS and a few data sets would allow you to look at a virtually infinite number of relationships, patterns, and phenomena. The challenge for the geographic researcher is finding the useful, relevant, effective, and interesting manipulations and analyses to perform.

Data Manipulation and Analysis

The distinction between data manipulation and analysis can be a little difficult to make in a GIS context. Often a simple manipulation of data (sometimes simply displaying the raw data) can enable analysis that takes place in the eye of the beholder. So we will not attempt to answer the question of where manipulation ends and analysis begins. There are several kinds of manipulations and analyses that are made dramatically easier when performed with a GIS:

1. ***Projection and coordinate transformation.*** As mentioned above, geographic information can come in various geo-referenced and non-geo-referenced formats. Most GISs are capable of converting geographic information from one coordinate system to another. Typically, the transformation of a data set from one coordinate system to another is just a matter of processing the X and Y coordinates through mathematical functions. This process is simplest with point data and gets more complex with line, polygon, and raster data. With line and polygon data, the transformation still operates on the points that make up the lines and polygons, then reconnects them using topological information in tabular form. In these situations, the density of points representing the lines and polygons can become a problem. For example, a minimum-bounding rectangle containing the conterminous United States in a geographic (lat-long) projection could consist of only four points. A reprojection of such a rectangle into an Albers Equal Area projection would result in a trapezoid with straight sides that should in fact have a curved top and bottom edge. This can be corrected by increasing the number or density of points making up the lines and polygons. When coordinate transforming raster data, you run into the issue of **resampling**. The space of a raster image is reprojected to a new coordinate system. This "space" is tessellated, typically with square pixels. The problem then is to determine what values those pixels should take. In resampling, the coordinates of the new pixels are sent through an inverse of the function used to perform the original transformation. This produces a location in the original image that is unlikely to land dead center in one of the original pixels. Consequently, one must choose from among several techniques available for determining the pixel value in the new image; three common resampling techniques are nearest neighbor, bilinear interpolation, and cubic convolution. If the raster data set is of a nominal

measurement level, then the nearest neighbor resampling method is the only appropriate choice.

2. ***Mathematical and logical manipulation of tabular data.*** Typically point, line, and polygon data consist of a geometric element (spatial reference and identification) and attribute information (tables linked to the geometric information). For example, line data representing roads might be associated with tabular information containing speed limits and traffic information, and polygon data of census tracts are associated with tabular information about population, areal extent, and median household income. This tabular information can be manipulated usefully, but also in erroneous and misleading ways. For example, the tabular polygon data with population and area attributes can be manipulated to create a new data attribute of population density by simply dividing the population column by the area column. These manipulations of tabular data can result from user judgments but also from mathematical and/or logical operations that produce new nominal, ordinal, or interval information.

3. ***Spatial aggregation and filtering.*** As we have suggested, it is sometimes desirable for various reasons to aggregate geographic information up to larger spatial units. Larger spatial units may represent a more appropriate resolution for a given geographic phenomenon, of course, but may also be preferable for display purposes, maintaining anonymity of survey respondents, more appropriate correspondence with other data, or ease of comprehension. Careful thought should be given to spatial aggregation, because GISs typically allow users to perform both appropriate and inappropriate aggregations. For example, suppose you have block-group census data with population counts, population density, percent of population that is Hispanic, and median household income as attributes. If you want to aggregate these block-group polygons to spatial units such as tracts or counties, you must give some thought as to what should happen to the block-group tabular attributes. You could sum the population count attribute to get an appropriate population count for tracts or counties. However, the other attributes are difficult if not impossible to retain at the aggregate level. You could recalculate population density if you either summed or recalculated the area of the new aggregate polygons. You could also recalculate the percent of population that is Hispanic with some effort. However, the median household income of the aggregate spatial units cannot be determined from the disaggregate information. In many GIS packages, this aggregation function (sometimes referred to as a "Dissolve") simply deletes the tabular attributes upon aggregation; other packages query the user as to what attributes to retain, and what logical or mathematical function to use to derive the new aggregate value (in the case of population in this example, it would be sum).

Raster data pixels can also be aggregated, and there are several ways in which to do this. Commonly the average value of the pixels being aggregated is used; however, there are many different ways to accomplish this task, including assigning the maximum or minimum value of any of the pixels being aggregated. **Spatial filtering** is an image processing technique that is typically applied to image or raster datasets. A filter (sometimes referred to as a **kernel function**) is an n by n window that is applied to each pixel of an image. The simplest example is a 3 by 3 pixel window that changes the data number of the pixel in question to the mean of the values in the 3 by 3 window. This is applied to every pixel in the image. A mean filter has the effect of "smoothing" an image. There are many different image filters, which use different mathematical functions, designed to do **edge detection**, remove a "salt and pepper" look, or serve other purposes.

4. ***Buffering and distance calculation.*** Measuring distance is one of the most fundamental capabilities of a GIS. It is a critical component of common functions like generating variograms, determining shortest paths on networks, and finding the nearest fire hydrant to the location of a given fire. A basic function of most GISs is the ability to create a **buffer** based on a fixed distance or a distance that could be derived from a variable attribute of points, lines, or polygons. An example is the way a logging company might buffer a road network in order to identify forest patches visible from the road. To minimize negative public perceptions of their clear-cutting activity, the company would avoid harvesting these patches. The buffer function of the GIS creates polygons at a specified distance from the roads. Of course, there has to be some thought as to how "thick" this buffer should be, or whether it should be a buffer of variable thickness that is larger for more heavily traveled roads. A GIS can calculate distances from points to points, points to lines, points to polygons, lines to lines, lines to polygons, and polygons to polygons. Any and all of these measurements can then be added to the tabular attributes of specified geographic features in the data set.

Another example of the utility of GIS distance calculations involves real estate prices and distance from the city center. Suppose you were interested in finding out if there was distance decay of real estate prices as they increased in distance from the central business district (CBD) of some city. You could overlay a point coverage of recently sold homes on a street network that contained the CBD. The GIS could calculate the shortest distance along the street network from each house to the CBD and add it to the attribute table of the house data set. A multivariate statistical analysis of the housing sales prices could then incorporate the new GIS-derived variable: distance to the CBD.

5. ***Overlay.*** Another fundamental function of GISs is the ability to compare two or more spatially referenced variables. There are numerous ways to conduct these kinds of comparisons, all of which are examples of the general concept of **overlay**. Given two raster data layers, most GISs can calculate the correlation between variables in the two layers and also add, subtract, or perform other mathematical functions on cells in the same geographic location that are expressed in the separate layers. A vector overlay may be performed between points, lines, or polygons.

The mathematical operations conducted as part of a raster overlay are part of the general concept of **map algebra**. The logic of vector overlay, in contrast, is derived from **Boolean logic**, the logic of combining sets. There are two major types of vector overlays, which represent the OR and AND statements of Boolean logic, respectively. The operation representing the OR statement is called a **union**. As shown in Figure 12.5, a union combines all of the geographic space of both layers, even if they are not co-incident in space, thus implementing the OR statement. The operation representing the AND statement is called an **intersect**. An intersect combines only the geographic space *shared* by the input and the intersect data layers, thus implementing the AND statement. When performed on polygons or lines, the layers are merged and new nodes are created at all crossings of polygon or line boundaries. The newly organized lines or polygons have the attribute characteristics of the two original layers. A specialized form of overlay with vector data is the **point-in-polygon** operation, which identifies spatial-set membership of a point layer within the polygons of a polygon layer. For example, one could perform a point-in-polygon operation on a U.S. "States" polygon layer with a point layer representing all the claimed "Elvis sightings" since his death. This could be accomplished in such a way that each point in the Elvis sightings data set has a new "State" attribute in its table of attributes, or it could be accomplished so that the attribute table of the States coverage has the new attribute of "Number of Elvis sightings" (with high numbers expected in Nevada and Tennessee!).

The details of how the principles of overlay are implemented vary between software systems. No matter the system, it is always worthwhile to read the documentation for each function to be certain that the theoretical logic expressed by your selected overlay operation matches the logic of your problem.

6. ***Spatial interpolation.*** As we discussed in Chapter 8, phenomena that are best represented as fields are measured only at a finite number of locations, typically points. This is especially common with physical geographic variables, such as rainfall, temperature, humidity, and ozone concentration. With such data, spatial interpolation is performed on the point coverage to generate the entire field of values—values intermediate to the sampled locations. A well-known example of this is the temperature map in the weather section of a newspaper. This is a field representation of temperature derived from a point network of temperature measurements (and a little bit of predictive modeling). There are many specific mathematical techniques for spatial interpolation, such as "inverse distance weighting," "kriging" (which comes in many flavors), "splines," and more. A sufficiently complete description of all of these techniques is beyond the scope of this book; references at the end of the chapter provide detail about them.

7. ***Spatial model building and spatial regression.*** Spatial model building and spatial regression analysis are some of the most sophisticated functions of GISs. Suppose you have a point network of rainfall measurements with information on rainfall, elevation, and temperature. You can build a simple regression model to predict rainfall from elevation and temperature. You can also apply the model to field data sets of elevation and temperature to produce a field representation of rainfall. Spatial model building often attempts to produce a representation of something that is not directly measurable. For example, suppose you wanted to produce a map of fire risk for the country of Portugal using variables like vegetation, slope, aspect, and distance to roads. You could obtain or derive a vegetation layer from the classification of a set of *Landsat* images, the slope and aspect layers from a digital

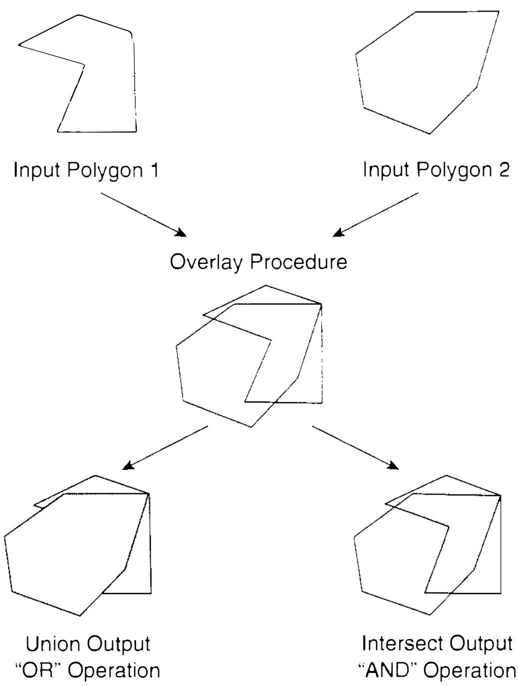


Figure 12.5 Union and intersection functions in a GIS. (Graphic by M. V. Gray. Reprinted with permission.)

elevation model (DEM—see Chapter 4) of Portugal, and the distance to roads from a vector coverage of the roads in Portugal. You could then calculate fire risk from any logical or mathematical combination of those input variables on a pixel-by-pixel basis. You could then input this model into a GIS to produce a raster representation of the abstract concept of "fire risk" for Portugal.

Review Questions

Geographic Information

- What is geographic information, and what are some sources of such information?
- What are some important characteristics of your phenomenon and the data you use to study it that you should consider when working with geographic information?
- How does the distinction between fields and objects relate to the distinction between physical and human geography?
- Why are issues of ontology important when working with geographic information, and what are some examples of ontological issues in geographic research?

Data Models and Data Structures

- What are data models and data structures?
- What are the vector and raster data models, and how does each fit different kinds of phenomena and data more or less appropriately?
- Why is it important when conducting research with geographic information to consider data models and data structures?

Remotely Sensed Geographic Information

- What are some different types of remotely sensed geographic information?
- How do spatial, temporal, and thematic scale express themselves in the context of remotely sensed geographic information? Provide specific examples of each.

Geographic Information Systems (GISs)

- What is a geographic information system, and what are its technological and human components?
- What are some methods and technologies for spatially referencing geographic information?
- What are some benefits of being able to query and display spatially referenced data with a GIS? Demonstrate your answer with a specific example.
- What are the data manipulation and analysis techniques of (1) projection and coordinate transformation, (2) mathematical and logical manipulation of tabular data, (3) spatial aggregation and filtering, (4) buffering and distance calculation, (5) overlay, (6) spatial interpolation, and (7) spatial model building and spatial regression? Provide specific examples of each.

Key Terms

active sensing: remote sensing of radiation that is originally emitted by the satellite and then reflected back from the earth surface; a good example is Radar

address matching: GIS operation in which a spatial database is used to georeference standard street addresses, ZIP codes, and so on

Boolean logic: the logic of combining sets, used as the basis for vector data overlay operations

buffer: GIS operation in which a band or zone of specified width is placed around selected vector features

classification: the creation of semantic systems, or ontologies, for organizing reality into meaningful types or units

conceptual model: mental or intellectual representation of geographic phenomena, including their spatial and nonspatial attributes, as understood by individuals or groups of people; the central conceptual distinction in geography is between "objects" and "fields"

coordinate system: spatial reference system of numerical units and rules that encodes location on the earth; latitude-longitude is the most common, but there are many

coordinate transformation: GIS data manipulation in which locational information in one coordinate system is mathematically translated into another

coverage: data layer in a GIS

data cube: large geographic information data set constructed from multiple spectral layers of remotely sensed information about the same portion of the earth, recorded at the same time

data model: simplified computer representation of a conceptual model of some phenomenon; the central distinction in geographic information is between "vectors" and "rasters"

data structure: the digital expression of a data model as represented in a computer

distinct number: the number of data points in a data cube stored for each pixel of earth surface; each data point is an intensity value in one narrow slice of the electromagnetic spectrum

edge detection: spatial filtering transformation designed to identify and highlight boundaries or discontinuities in a raster data layer

fields: fundamental conceptualization of geographic phenomena as continuous surfaces (usually two-dimensional); much more common in physical than in human geography, it is usually contrasted with "objects"

geographic information: information that is spatially referenced to the surface of the earth; nowadays, the term usually implies information in digital form

geographic information science (GISci): the discipline, or collection of disciplines, that emerged during the 1990s as the scientific study of geographic information, including its representation and use in computers, human minds, and societies

geographic information system (GIS): the computer hardware and software used to store, query, display, manipulate, and analyze geographic information

geoid: the average surface around the planet Earth that is used as its baseline shape; it is a little more accurate as a model of the planet's shape than is a strict oblate spheroid

geo-referenced information: information that is spatially referenced to an earth coordinate system

Global Positioning System (GPS): electronic technology for determining the two- or three-dimensional location of any point on or near the earth surface, based on a set of satellites and computer software that triangulates location on the basis of time information in the satellite signals

granularity: synonym for resolution

interoperability: the problem of effectively communicating geographic information among different people, cultures, disciplines, and information systems; typically used in the context of digital information systems

intersect: GIS operation applied to overlaid vector data in which common values are identified that are present in all layers

kernel function: the *n* by *n* window of cells in a raster data layer to which spatial filtering transformations are applied in order to convert the cells to a single common value

lines: entities modeled as one-dimensional features in a vector data model

map algebra: the set of mathematical GIS operations, such as addition or subtraction, that can be applied to overlaid raster data

objects: fundamental conceptualization of geographic phenomena as discrete entities (of any dimensionality); common in both physical and human geography, it is usually contrasted with "fields"

oblate spheroid: geometric term for a sphere that is "flattened"; it is very nearly the shape of the planet Earth, which has a pole-to-pole diameter 42 km (26 miles) less than its equatorial diameter

ontologies: systems of concepts or classes of what exists in the world; somewhat different forms are found in individual minds, cultural belief systems, and computer databases

overlay: GIS operation in which two or more data layers based on the same area of earth surface are superimposed in order to be compared

passive sensing: remote sensing based on recording solar radiation reflected from the earth surface or other types of radiation emitted from the earth; a good example of emitted radiation is that from fires or electric light bulbs

pixels: approximations of fields on digital image displays as checkerboard coverages of small regular "cells," usually square; the computer-screen analogue to remotely sensed image data rasters

point-in-polygon: GIS operation applied to overlaid vector data in which a layer of points is intersected with a polygon layer

points: entities modeled as zero-dimensional features in a vector data model

polygons: entities modeled as two-dimensional features in a vector data model

raster data model: data model that represents geographic information as a continuous two-dimensional field consisting of a regular tessellation of small cells, typically square; the typical data model for satellite remotely sensed imagery

remotely sensed geographic information: information about the (near) earth surface in the form of analog or digital recordings of patterns of electromagnetic energy in one or more portions of the spectrum; it includes aerial photography and satellite imagery

resampling: GIS data manipulation in which new values are determined for raster data layers that are coordinate transformed

resolution: term for spatial, temporal, or thematic scale, particularly used in the context of analysis scale with digital geographic information; synonym of granularity

spatial aggregation: GIS data manipulation in which information at one spatial scale is transformed into some larger scale by combining areas

spatial filtering: type of spatial aggregation in which raster information is transformed by modifying cell values within a particular defined area according to a mathematical or computational formula

spectral resolution: the degree to which remotely sensed information can pick up precise portions of the electromagnetic spectrum rather than broad portions; it is an expression of thematic scale because it greatly influences the specificity with which particular geographic features can be identified

tessellate: to "tile" a two-dimensional (planar) surface with a coverage of small regular cells; equilateral triangles, squares, and regular hexagons are the three regular polygons that can tessellate a planar surface exhaustively without overlap

themes: the characteristics of human and natural phenomena other than space and time that geographers measure as variables and store as attributes in a GIS

union: GIS operation applied to overlaid vector data in which values are identified that are present in any of the layers

vector data model: data model that represents geographic information as meaningful geometric objects of varying dimensionality

volumes: entities modeled as three-dimensional features in a vector data model

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