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APPLICATION OF SPATIAL TECHNOLOGIES IN WILDLIFE BIOLOGY

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INTRODUCTION

The Information Age is here, and technology has a large and important role in gathering, compiling, and synthesizing data. The old adage of analyzing wildlife data over "time and space" today entails using technologies to help gather, compile, and synthesize remotely sensed information, and to integrate results into research, monitoring and evaluation. Thus, resource managers must understand how to use these technologies, especially for evaluating and assessing land and resource conditions at different scales, such as site, watershed, sub-basin, and basin levels. This chapter explores spatial technologies useful to wildlife managers for acquiring, compiling, and interpreting data. These technologies include: geographic information systems (GIS), global positioning systems (GPS), and using remotely sensed data, including Landsat Imagery and Forward-looking Infrared (FLIR). This chapter also highlights the need to understand data accuracy and Internet applications.

Today's issues and their complexities have a tendency to overwhelm resource managers in a sea of data. Most resource agencies are awash in data, but managers still find themselves with a lack of information. Spatial technologies provide tools to incorporate and analyze large data sets in a meaningful manner with production of useful information. Data can be converted or displayed by locations or across a landscape and displayed as charts, drawings, or as maps. These technologies provide a way to assess and depict complex relationships among variables, which is useful for incorporating scale and hierarchy concepts into ecosystem-based management assessments (O'Neill 1996) and to help examine environmental impact significance (Antunes et al. 2001). Additionally, they allow spatial depictions of theoretical concepts, such as change in total redundancy of ecosystem functions (Fig. 1). The technologies presented here also allow others to see how decisions are made, thus leaving a foot print(s) in the decision making process to follow. However, as with any analysis and modeling tools, uses of spatial technologies are only as accurate and reliable as the underlying data. Spatial tools on their own cannot improve accuracy, precision, and bias of information.

Spatial technologies should be considered as tools to assist resource managers with mapping. Maps are as important to the manager as calculators and vehicles. Using spatial technologies can provide timely information in usable formats for aiding decision-making, but these

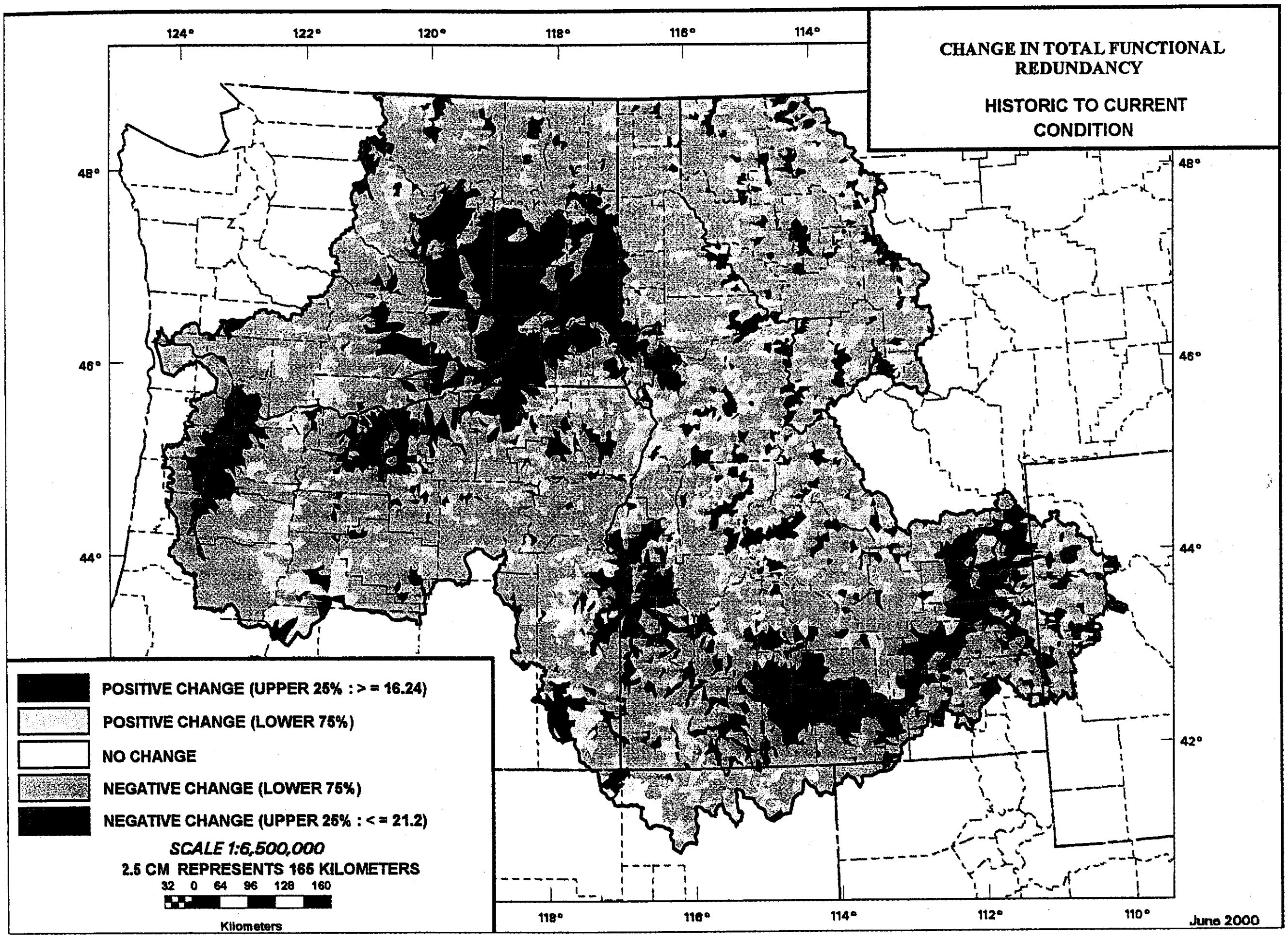


Fig. 1. Using GIS, Marcot et al. (2002*b*) depicted the concept of Total Functional Redundancy for the Columbia River Basin.

tools should not be viewed as making the final decisions *per se*. Spatial technologies, like GIS, are frequently described in terms of hardware (computers and work stations) and software (computer programs). Typically, more computing power (speed and memory) in combination with large computing storage (disk space) is preferred. Workstations do most of the heavy lifting in handling large and/or complex data sets. Peripherals such as tape storage and retrieval systems, and CD-ROM and DVD-RAM devices are required to effectively transcribe data in and out of systems.

Building and Using a GIS

Many factors should be considered when designing and developing a major GIS application or its' implementation to ensure success and sustainability. These include, but are not limited to those identified.

- *Establish clear objectives*—The purpose and function of the system must be clearly defined so that managers, system developers and operators, and product users know the system's capabilities and limitations. Establishing clear objectives will lead to building a system to deliver answers to management resource questions.
- *Design the system to be driven by demand*—Long-term sustainability and funding for a system can only be assured if the system meets user's needs for information (Falloux 1989). Demand for system services and support should keep the development and subsequent modification and upkeep of the system focused on its objectives and will promote its use in the decision-making process.
- *Coordinate initiatives and avoid duplication of efforts*—GIS systems are most efficiently developed and effectively used when there is strong coordination between relevant agencies and organizations. Scarce resources can be stretched furthest when there is little overlap or duplication in data development activities. A common problem occurs when different agencies develop similar databases, which inevitably are inconsistent because of possible different data sources, scales, classification systems, or simply different interpretations of facts, patterns, and trends.
- *Develop the system from data, not interpretation*—Much unnecessary duplication of effort has occurred because GIS databases have been developed based on interpretation of data instead of base data from which different interpretations can arise. An example is the multiple GIS maps developed in the Pacific Northwest of the United States to map old-growth forests. Instead of mapping base attributes of forests such as age, mean tree diameter, canopy structure, etc., from which various definitions of old-growth could then be

applied, many organizations chose to just map "old-growth forests" and skip the base data layers. When their definitions differed, the maps were not comparable, and when definitions changed, much GIS work had to be redone or abandoned, wasting time, money, and effort.

- *Develop a data strategy*—Databases providing the GIS foundation must be credible and reliable. Decisions must be made whether or not to use existing databases from other sources or to develop the information from primary sources. Standards should be established for including data in the databases. This helps ensure that information from different sources is technically and thematically compatible. Interoperability, or the ability to use databases directly from one system to another or from one application to another without major conversions or recompilations, is an important factor to consider in the strategy (Prévost and Gilruth 1997). An essential step in the data strategy is development of a data catalog that defines and describes the elements. This metadata, or supra level data about the data, enables a user to decide on the quality and fitness of the information to be used in an analysis. Decisions must also be made about geographic scale of analysis, thematic classification systems, and the relevancy of the current information.
- *Develop a realistic cost estimate*—Building a GIS is more than buying the necessary computer hardware and software (World Bank 1995). Significant efforts and resources are required to build an institutional framework, develop and acquire data, and develop human resources to manage, operate, and use the system. A guideline for estimating relative costs for a GIS initiative is the 20-80 rule. This suggests that 20% of the total cost is for system hardware and software and 80% is for data development activities, institutional costs, and other operating expenses.
- *Build institutional support for the initiative*—Having institutional support and management "buy-in" to the initiative is the single most critical factor for successful planning and development. Enthusiastic acceptance for the initiative from those in an organization responsible for making decisions and allocating resources helps ensure that adequate support is available and that GIS becomes integrated into mainstream decision-making processes. Integrating GIS services with other aspects of an organization's functions, rather than developing them as a stand-alone sideline activity, not only increases their general utility, but also makes them less vulnerable to disruption during times of organizational or management changes. Having the GIS operation prominently located in an organizational structure gives it more recognition as a valuable asset and raises its standing in times of competition for scarce institutional resources. GIS systems are not luxuries but necessities for doing spatial-based land and resource planning, and they should be viewed as tightly woven into assessment, decision-making, and monitoring activities.
- *Establish management and technical steering committees*—Involving a broad base of management and technical expertise in early design stages as well as later operational stages helps obtain a wide range of ideas about how best to accomplish the organization's stated objectives for the system. Involving expertise as advisory groups helps build commitment and support from a more diverse community of interested stakeholders who then share the responsibility of making the initiative a success. Such advisory groups foster better collaboration and cooperation among agencies and departments and help ensure that common data strategies and standards are implemented.
- *Use appropriate technology*—It may seem obvious, but selecting inappropriate technology is still a major cause of failure and cost overruns for well-intentioned GIS initiatives. GIS hardware and software must be appropriately selected to match not only kinds of information to be handled, but also kinds of analysis to be performed, and volume of the information in the databases. For example, it would be inappropriate to select a vector-based system if most information to be processed was raster-based satellite imagery. It would also be inappropriate to select a small, single-user desktop computer system to manage terabytes of information in a national database.

Factors Needed to Sustain a GIS

An often-overlooked aspect of establishing GIS capabilities is a plan or strategy for ensuring that an initiative can be sustained once it has been implemented. Many systems have failed because they have not accounted for the essential factors necessary to sustain a GIS system after its initial development. These factors include but are not limited to those identified.

- *Education and training*—For many managers and decision-makers, integrating spatial information and analysis into decisions and plans is not a familiar process. Many decision-makers need to be informed about how GIS tools and services can assist them in their work (van Genderen 1991). The GIS initiative should include a strategy for ensuring that senior managers and decision-makers have an intimate understanding of and direct experience with how these tools can support their activities. Also, there should be provisions for training those directly responsible for managing and operating the GIS capabilities and for training users on how to access and use the information and analysis functions.
- *Provision of interim products*—During early stages of developing a GIS capability within an agency or a program, it is important that interim products are provided to managers (i.e., those providing the authorization and resources for the initiative) to spark and sustain their interest, enthusiasm, and commitment. A long development period with nothing visible to show for the effort frequently causes managers to lose focus on the initiative and to shift emphasis and resources to other initiatives with more immediate paybacks.
- *Responsiveness to the needs of users and decision-makers*—The support provided by the system must continue to be valuable and vital for decision-making processes (Prévost and Gilruth 1997). If decision-makers and other users of the system are able to perform their functions more effectively and efficiently

with information and services provided by the system, they are more apt to ensure the support needed to sustain its operations. Benefits gained from services of an established system, in terms of time saved, cost avoidance of ill-informed decisions, and economic, social, and political benefits achieved from well-informed decisions, should be expressly demonstrated and documented.

- *Integration of scientific information into policy dialog*—GIS analysis can provide information in a structure and manner to directly and positively affect policy discussions. To be useful to decision-makers, spatial information should be more than simple lists or maps of "facts," and should be digested in a way to suggest impacts, consequences, and trade-offs. With environmental issues in general, and wildlife management issues in particular, the chasm that exists between science and policy can frequently be narrowed by skillfully using spatial analysis tools and techniques to bring scientific information into the realm of policy discussions. To illustrate, decision-makers deciding on the fate of a wildlife species, such as the spotted owl (*Strix occidentalis*), need to know more than how the species is spatially distributed. They need to know how this spatial distribution is related to environmental, social, and economic factors and the impacts and benefits of alternative management scenarios. However, the complexity of integrating scientific information into policy dialog and decision-making processes is not simple and should not be underestimated.
- *Ensure adequate resources*—Once established, recurrent resources are required to sustain the on-going operation, management, data development, and data documentation activities. Regular provisions in budgets would be needed for costs associated with hardware and software maintenance and upgrades, updates to databases, and maintaining staffs. Without adequate resources, systems become antiquated and outdated, and no longer effectively support their intended functions.

The first spatial technology addressed in this chapter is GIS, which is a general-purpose technology for handling geographic data in a digital form. GIS has the capability to: (1) pre-process large amounts of data into a form suitable for analysis and evaluation; (2) support models that perform analysis, calibration, forecasting, and prediction of spatial relations of many variables; and (3) post-process results to produce tables, reports, and maps (Goodchild 1993, Peuquet et al. 1993, Franklin 1995, Theobald 2001). Koeln et al. (1996), Korte (2000), Longley et al. (2001), and Rigaux et al. (2001) presented technical descriptions of GIS. Bettinger (1999) presented the challenges and opportunities associated with GIS implementation in field offices.

Box 1. What is a spatial relationship?

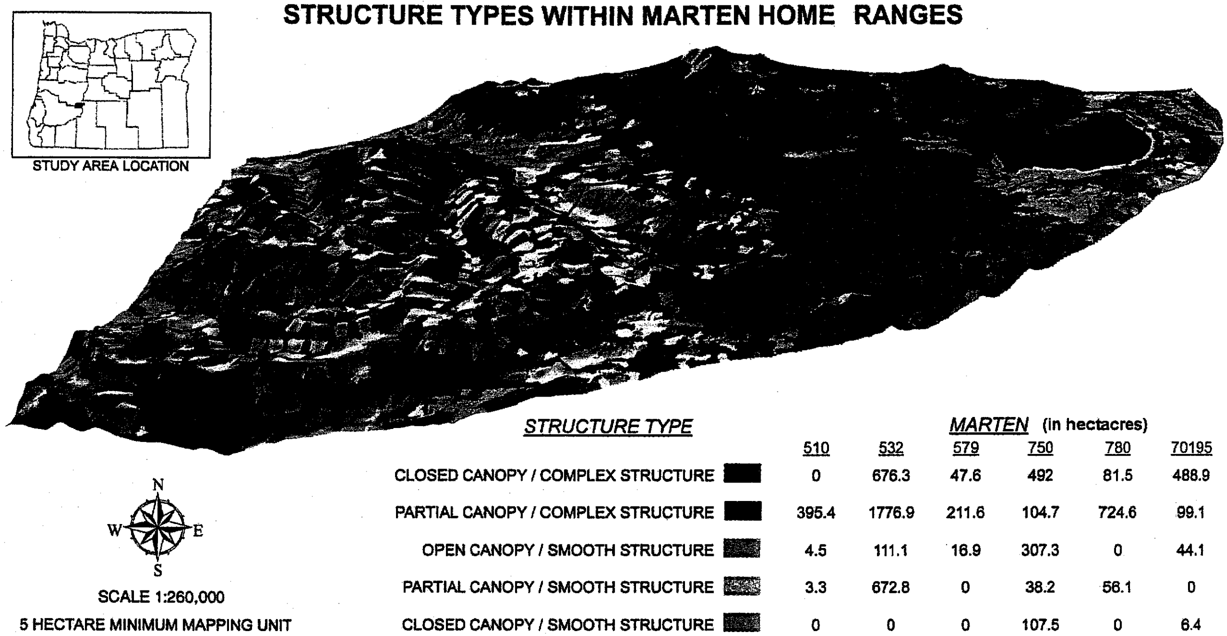
Spatial relationships may be important in understanding the resources of concern when developing habitat management strategies (Schroeder et al. 1998). Spatial relationships describe the association among landscape features and may be characterized in both topological and directional aspects. Topology uses methods that develop and remember associations among landscape features. The work of mathematicians, cognitive scientists, and designers of software has driven research into spatial relationships for GIS. In GIS it may not be sufficient to know just the position of a landscape feature, but also to know how the landscape feature relates to other features in the same (or other) databases. For example, it may not be sufficient to just be able to locate a patch of optimal habitat; it may also be important to locate other patches of good or optimal habitat nearby.

Some examples of spatial relationships include:

- polygons that share a common boundary (e.g., adjacent polygons),
- polygons of a certain type (e.g., optimal habitat) nearest to other specific polygons (e.g. proposed harvests),
- polygons that overlap other polygons (e.g., the intersection of soils and timber stands),
- lines that cross one another (e.g., roads that cross streams),
- lines that logically flow into one another (e.g., stream networks),
- lines that are within a certain distance of other landscape features (e.g., roads within a certain distance of streams),
- points contained within polygons (e.g., bird point sample locations within timber stands), and
- points that can be seen from certain other points (e.g., as in defining viewsheds).

USING GIS IN THE WILDLIFE PROFESSION

Prior to 1950, vegetation maps were tediously drawn by hand and wildlife biologists interpreted the maps in terms of habitat for wildlife, typically game animals. The availability of aerial photography and then satellite imagery later gave biologists a way to more accurately and consistently analyze habitats across broader landscapes. For example, in the early 1970s, Schuerholz (1974) quantified forest edge habitat from aerial photographs and Cowardin and Myers (1974) identified and classified wetland habitats from remotely sensed images. In the later 1970s and 1980s, as computers became more available and capable, vegetation maps were transcribed into digital images and habitat analyses became highly automated (e.g., Marcot et al. 1981, Mead et al. 1981, Mayer 1984, Burroughs 1986, Brekke 1988). Today, GIS is an indispensable tool for analyzing historic, current, and potential future habitat conditions for wildlife (Fig. 2), and for assessing the spatial relationships among landscape features. GIS is widely used for evaluating cumulative effects of management actions and potential effects of alternative management decisions on wildlife habitats, populations, and communities.



STRUCTURE TYPE	MARTEN (in hectacres) 510	532	579	750	780	70195
CLOSED CANOPY / COMPLEX STRUCTURE	0	676.3	47.6	492	81.5	488.9
PARTIAL CANOPY / COMPLEX STRUCTURE	395.4	1776.9	211.6	104.7	724.6	99.1
OPEN CANOPY / SMOOTH STRUCTURE	4.5	111.1	16.9	307.3	0	44.1
PARTIAL CANOPY / SMOOTH STRUCTURE	3.3	672.8	0	38.2	56.1	0
CLOSED CANOPY / SMOOTH STRUCTURE	0	0	0	107.5	0	6.4
GRASS-FORB / SHRUB / SAPLING	0	7.9	8.6	208.4	0	101
SPARSE VEGETATION	0	80.9	0	0	0	0.9
OPEN WATER	0	1304.9	1.1	0	19	2.9
HOME RANGE SIZE :	**403.2**	**4630.8**	**285.8**	**1258.1**	**881.2**	**743.3**

Fig. 2. GIS allows integration of data; American marten (*Martes americana*) home ranges are overlaid on structural habitat conditions and topography (Northwest Habitat Institute, Corvallis, Oregon, USA).

GIS and Modeling Wildlife-habitat Relationships

One of the most common uses of GIS in wildlife management is in analysis of amounts, patterns, and trends of habitat changes for individual wildlife species. For example, McComb et al. (2002) used GIS to model potential habitat of northern spotted owls (*S. o. caurina*) at landscape scales in the Pacific Northwest of the United States. Dettmers and Bart (1999) applied GIS to predict forest songbird habitat in southern Ohio. Carroll et al. (1999) used presence data to construct and validate spatial habitat models of fisher (*Martes pennanti*) in central Oregon. Knick and Dyer (1997) used GIS to analyze black-tailed jackrabbit (*Lepus californicus*) habitat in southwestern Idaho. O'Neil et al. (1995) depicted and mapped all of Oregon's wildlife-habitat types using GIS. Following procedures used by O'Neil et al. (1995), Kiilsgaard and Barrett (2000) created the first wildlife-habitat types map of the entire Pacific Northwest in the United States. Many other examples occur in the literature.

GIS-based wildlife–habitat relationships models use variables such as slope, aspect, and vegetation structure to depict habitat categories and habitat quality for individual species. Variables used are based on factors shown or expected to influence quality of habitat selected by particular species. These models are usually based on professional judgment and experience, or on empirical research. Bettinger (2001) outlined many of the challenges facing integration of wildlife models with remotely sensed imagery and data related to forest structural conditions. Dussault et al. (2001) cautioned that existing forest cover maps might not be adequate for evaluating wildlife habitat suitability without an examination of the correlation between mapped forest features and structural conditions used by specific wildlife species or species groups.

Other types of models for evaluating habitat quality also have been integrated with GIS. For example, Clevenger et al. (2002) integrated expert-based models to help identify and plan for wildlife habitat corridors, Raphael et al. (2001) integrated Bayesian belief network models of species habitat suitability into GIS analyses, Guisse and Gimblett (1997) evaluated state park recreation conflicts by integrating a neural network model with GIS, and Rickel et al. (1998) used a fuzzy logic model in conjunction with GIS to evaluate wildlife habitat quality. The main objective of these approaches has been to develop useful tools for resource managers charged with identifying locations of important areas for wildlife when empirical information is lacking. GIS helps facilitate this process by providing a representation of the spatial features of a landscape into the habitat quality evaluation.

Statistical analyses have also been integrated with GIS processes to evaluate quality of wildlife habitat. For example, Clark et al. (1993) integrated a multivariate analysis of female black bear (*Ursus americanus*) habitat into a GIS model whereas Pereira and Itami (1991) used results of a logistic multiple-regression study of the Mt. Graham red squirrel (*Tamiasciurus hudsonicus grahamensis*) in their GIS model of habitat for the subspecies. Software developed by a variety of organizations is increasingly becoming open to integration. As a result, almost any wildlife habitat quality model that can be described in terms of mappable habitat features can be developed with GIS.

Some researchers have taken integrated GIS-based wildlife-habitat relationships models into National Forest planning processes. This represented a distinct change in forest planning by complementing existing economic or commodity-production objectives with wildlife habitat objectives. Bunnell (1974), Mead et al. (1981), and others pioneered early applications of this type. Later, Hof and Joyce (1992, 1993) and Hof et al. (1994) integrated wildlife habitat concerns in mathematical forest planning models. Models integrating wildlife habitat relationships with forest planning processes have focused on elk (*Cervus elaphus*) in Oregon (Bettinger et al. 1997, 1999), birds in the northwest (Bettinger et al. 2002), birds in the Midwest (Nevo and Garcia 1996), ruffed grouse (*Bonasa umbellus*) habitat in the Midwest (Arthaud and Rose 1996), red-cockaded woodpecker (*Picoides borealis*) habitat in the southeast (Boston and Bettinger 2001), northern flying squirrel (*Glaucomys sabrinus*) in western Oregon (Calkin et al. 2002), spotted owls in Washington state (Hof and Raphael 1997), and late-successional habitat in Oregon (Sessions et al. 2000). Measures of biodiversity also have been integrated into forest planning efforts (Kangas and Pukkala 1996). Other habitat-related concerns can also be included in forest planning processes, such as the desire to develop and maintain contiguous core areas of older forest (Öhman and Eriksson 1998, Öhman 2000), and development of connected habitat corridors (Sessions 1991, Williams 1998).

GIS and Modeling Populations

Spatially explicit wildlife population models consider 2 factors of importance to the estimation of populations: species-habitat relationships, and habitat arrangement over space and time. These population models usually are developed for one (or only a few) species; simultaneously modeling habitats and populations of multiple species across a landscape remains a significant challenge (Turner et al. 1995). Liu et al. (1995) provided an example of the use of a spatially explicit population model in GIS to examine the impact on a nontarget species, Bachman's Sparrow (*Aimophila aestivalis*), of a forest plan developed for other goals. The model results helped managers examine how sparrow population density and distribution might react to planned management activities, such as whether resulting sparrow populations are of a size that meets the minimum management goal for the species, or whether the populations are sensitive to certain projected landscape characteristics. Another example is the work by Mladenoff and Sickley (1998) who used GIS to assess potential population sizes of gray wolf (*Canis lupis*) in the northeastern United States.

GIS has been used as an integral part of population viability analysis (PVA) (Akçakaya 2000). Kingston (1995) reviewed the use of population viability models within a GIS environment. Using GIS for PVA typically entails modeling vital rates (survival, reproduction) and population parameters (e.g., dispersal) of individuals of a species to calculate population size and distribution over time, and rates of population change. To model PVA spatially, data are required on spatial structure (location, size, and quality) of habitat patches that a particular species might use. This allows land managers and planners to evaluate how management practices may affect the probability of species distribution, trends, and extinction. Brook et al. (1999) compared 4 PVA analysis processes, including ones

Box 2. Integrating habitat relationships into a forest planning process.

We illustrate with an example provided in Bettinger et al. (2001) to demonstrate the process of integrating habitat relationships into a forest planning process, Wildlife habitat goals can be either qualitatively or quantitatively defined. Quantitative goals can also reference spatial information provided by GIS databases, allowing spatial goals to be developed. Spatial goals may include configurations such as requiring minimum patch sizes, or complementary habitat types and, thus, may indicate that, for optimal benefit to a particular species, one type of habitat should be placed next to another. Great gray owls (*Strix nebulosa*), for example, prefer early seral stage forests (clear cuts) for foraging, yet these areas should be adjacent to single-story open-canopy forests containing snags or large trees with broken tops.

Within a forest-planning environment, one can use a complementary patch goal (one where a patch of one type [e.g., nesting habitat] must be next to a complement—a patch of another type [e.g., foraging habitat]) to guide development of a forest plan that seeks to provide the greatest amount of habitat over time, while also achieving other economic or commodity production goals. The criteria used to measure whether the objective was achieved consist of measuring the percentage of land in each planning period that meets habitat requirements of great gray owls. A further quantification of the habitat goal is required and Bettinger et al. (2001) assumed that maximization of the percentage of land in patches $\geq$20 ha and $\geq$90 years old adjacent to patches $\geq$10 ha and $\leq$10 years old would suffice. In addition, a few practical constraints were added to the forest planning problem: clear cuts were limited to $\leq$48.6 ha, minimum clear-cut harvest ages were 40 years, a minimum volume of about 19,000 m^3 per 5-year period was required from the landscape, and only one regeneration harvest was allowed during the planning horizon.

A heuristic planning technique (i.e., one that locates good, feasible solutions to problems, yet not necessarily the best solution to problems), *tabu* search (a deterministic search process based on remembering choices that have been made), was used to develop the forest plan using a spatial arrangement of great gray owl habitat (Fig. 3). The amount of timber volume produced per 5-year planning period averaged 9.5 million board feet (60,000 m^3) (Fig. 4). Harvest volume was relatively high in the last few time periods because some cutting was required to create early seral patches to complement the older forest patches.

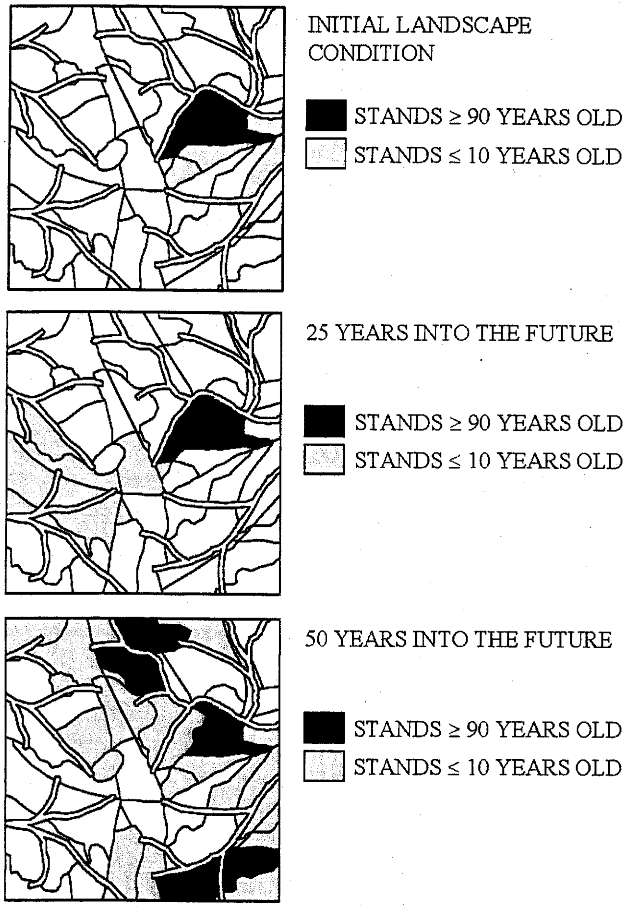


Fig. 3. Spatial arrangement of great gray owl habitat consisting of early successional stands and stands ≥90 years old over a 50-year planning period.

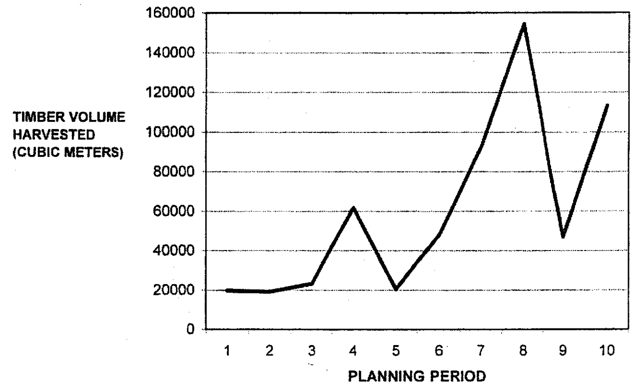


Fig. 4. Timber volume harvested over 50 years at 5-year planning increments.

that use spatial or mapped representations of populations, and concluded that subtle differences among models can affect results. Thus, the modeler should understand the mechanisms of the models used, and coach decision-makers on appropriate interpretation of the results.

Beyond assessing populations and viability, Allen et al. (2001) used GIS gap analysis to model viable populations of mammal species and concluded that defining minimum critical areas for mammals was a useful way to produce maps of critical unprotected sites. Hof and Raphael (1997) developed a geographic model to optimize allocation of northern spotted owl habitat in Washington State. Optimization model parameters included adult survival, fecundity, and occupancy of sites. Some authors have even integrated assessments of population genetics with GIS. For example, Ji and Leberg (2002) evaluated genetic diversity from a regional perspective using GIS. Also, since intensive ground surveys cannot keep pace with the rate of land use change in some areas of the world, presence-absence models are being developed for use in GIS, in conjunction with remote sensing and other technologies, to allow one to map the potential distribution of species at large spatial extents (Osborne et al. 2001, Kilgo et al. 2002).

GIS and Conservation of Wildlife Communities

Another use of GIS in wildlife management is delineation and conservation of wildlife and ecological communities. Delineation of "hot spots" (areas of high species richness or centers of species endemism or rarity) (Dobson et al. 1997, Ceballos et al. 1998, Griffin 1999) has become popular for specifying areas with wildlife and plant assemblages and communities potentially needing protection. Mapping species-rich hot spots has been used to delineate potential protected areas or reserves (e.g., Bójorquez-Tapia et al. 1995). Some spatial algorithms or processes used to delineate hot spots have been rigorously evaluated. For example, Araújo and Williams (2001) discovered bias toward marginal populations when delineating complementary hot spots, and NCASI (1996) reported that results of richness hot spots could be highly sensitive to the accuracy of the underlying distribution maps of individual species.

The "National Gap Analysis" Program (GAP) took delineation of conservation hot spots further by intersecting areas of high species richness with a set of land use allocations under the goal of identifying areas of high richness that may lack protection (Scott et al. 1993). GAP provides an assessment of the extent of representation of native species' habitats and communities across a landscape. Those species or communities not adequately represented in protected status on public lands can be viewed as "gaps" in conservation networks (Pearlstine et al. 2002). The process of identifying "gaps" has been aided by dividing analysis areas into segments to account for geographic variation and to help cover broad geographic areas (Scott et al. 2001). For example, the Florida GAP project is a geographically extensive analysis. One of the objectives of this project is to provide interested stakeholders with GIS databases related to the status of terrestrial vertebrate species and their habitats. Landsat Thematic Mapper satellite imagery is used, as are the National Wetlands Inventory GIS databases, other available databases (e.g., soils), aerial photography, and on-the ground surveys (Pearlstine et al. 2002) to accomplish this objective.

GIS also has been used to design potential reserves or protected areas. One of the fundamental issues for biologists and managers is selection or proposal of areas that should be conserved. Several techniques have been developed to select optimal reserve designs, each using GIS databases to guide selection of reserve areas. Wildlife habitat relationships can be used to delineate areas of special concern, such as the "corridor suitability" GIS database created for Maryland's Green Infrastructure Assessment (Weber and Wolf 2000). Here, GIS databases representing land cover, stream networks, roads, slope classes, aquatic community conditions, and other variables were used to create a database that described the suitability of areas to potentially serve as corridors for wildlife movement. This database was then used in a model that delineated the least-cost pathway between core wildlife management areas.

Other researchers (e.g., McDonnell et al. 2002, Nalle et al. 2002) devised mathematical algorithms to most efficiently design nature reserve systems to meet biodiversity objectives. In addition, reserve area redundancy (ReVelle et al. 2002), complimentarity (Williams et al. 2000), and representativeness (e.g., Mackey et al. 1988, Powell et al. 2000, MacNally et al. 2002) have been discussed in the literature and demonstrated through use of GIS processes. Dobson et al. (2001) advocated integrating strategies and objectives to simultaneously meet multiple needs for people and species.

Efficient identification of potential reserve areas with GIS processes has allowed policy makers to quantitatively address a number of reserve management issues. For example, should reserve areas represent an array of community, productivity, or ecosystem classes as Stokland (1997) suggested for bird and insect conservation in boreal forest reserves of Norway? Should reserve areas be established mainly for species richness, species rarity, or for other objectives such as balancing requirements of rare species conservation by establishing corridors with a broader biodiversity conservation perspective (Fig. 5)? Williams et al. (2000) suggested that more biodiversity could be protected if the few species that attract the most popular support (flagship species) had distributions that covered the broader diversity of organisms across a landscape. Should some level of redundancy be built into reserve areas to guard against potential losses from major disturbance events? Finally, should reserve areas be complementary to one another to efficiently and cost-effectively set aside the least amount of land area with highest biological opportunity cost? Each of these questions can be addressed with the appropriate GIS databases and reserve selection processes.

GIS and Risk Analysis

Another major trend is use of GIS to conduct risk analysis and management. GIS tools provide ways to pose "what if" questions to examine predicted results of potential actions. An example is work by Wright and Tanimoto (1998) who used GIS to set priorities for land conservation by integrating analyses of habitat diversity, ownership, and development into an overall risk analysis. Managers of both public lands and conservation organizations often are interested in purchasing land or acquiring conservation easements. Budgets are usually limited, which presents a need to efficiently spend time and money. Wright and Tanimoto (1998) developed a system for evaluating habitat diversity within a specified proximity of each delineated land unit. The units of privately owned and undeveloped land with highest habitat diversity were considered priority candidates for acquisition.

Llewellyn et al. (1996) used GIS in a decision support model to prioritize wetland sites for restoration along the Mississippi River floodplain. One of the most important phases of the project was to develop a set of GIS databases for the entire ecosystem. In addition, a set of high-resolution GIS databases was developed for a single watershed to generate more detailed land-use conversion statistics and to demonstrate the feasibility of a landscape restoration planning process. Included in the planning process was a method for prioritizing wetland forest patches and other areas suitable for reforestation and connection via corridors.

Other decision-support GIS models have been designed to integrate processes, such as expert systems (Fedra 1995), into evaluation of management alternatives. The main goal of these efforts may be to facilitate examination

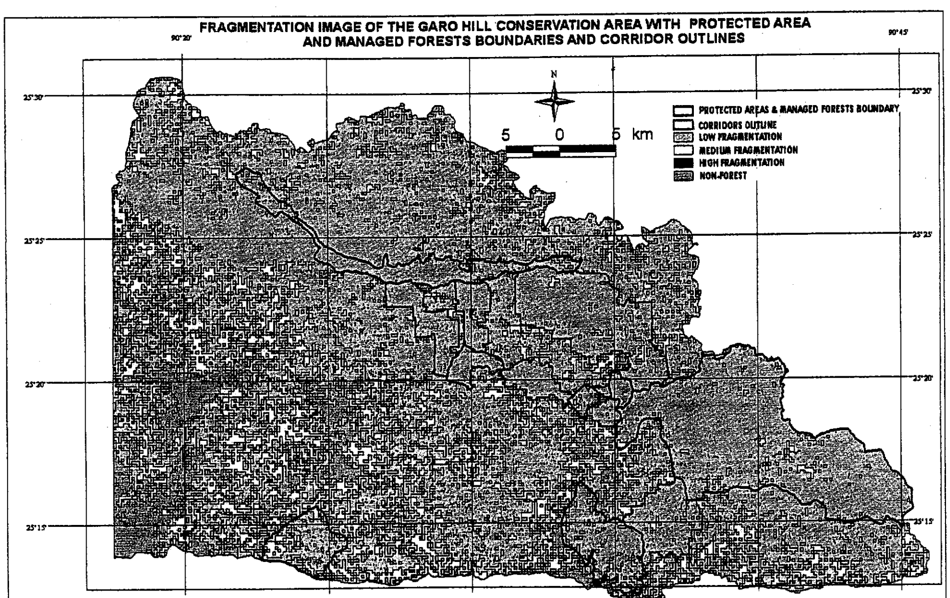


Fig. 5. Use of GIS analysis of fragmentation of elephant (*Elephas maximus*) habitat in Meghalaya, northeastern India, to help delineate habitat corridors (Marcot et al. 2002*a*).

of one of the side effects of the decision-making process that many managers have when overwhelmed with data and analysis; the need to describe the uncertainty and risk associated with potential decisions.

GIS in the International Community

GIS is becoming a commonly used tool to study, understand, and manage environmental issues at local, regional, national, and international levels. Initiatives, which are of particular interest at the international level, are the spatially related information programs of the United Nations Environmental Programme (UNEP). The first is UNEP's Global and Regional Integrated Data (GRID) program. From its conception at UNEP headquarters in Nairobi, Kenya, GRID has evolved into a still expanding network of environmental data centers around the world, each with a particular regional focus but coordinated in their efforts at a larger global scale. The centers facilitate and promote the development, documentation, archiving, and dissemination of environmental GIS and statistical information. With a concentration on environment, conservation, and natural resource issues, the centers' databases and analytical capabilities are designed to assist researchers and analysts in making reliable environmental assessments in support of public policy dialog (UNEP-GRID Europe 2003).

UNEP-GRID centers typically have data sets and information on environmental issues such as biodiversity, ecology, climate, soils, land cover, hydrology, and human impacts, as well as general information concerning geology, atmosphere, oceans and political boundaries. Partly because of its association with prominent information sources such as NASA, NOAA, and USGS, the North American node of UNEP-GRID, at Sioux Falls, South Dakota, has a prominent role in the larger network of centers, providing a number of data sets on a global scale (UNEP-GRID North America 2003). Much of the information is available online through the Internet and can be downloaded to individual GIS workstations.

The other prominent UNEP hosted initiative, relating to spatially referenced environmental information and analysis, is the World Conservation Monitoring Centre (WCMC). In 1988, IUCN (International Union for Conservation of Nature and Natural Resources), WWF (World Wildlife Fund for Nature), and UNEP founded a nonprofit organization, the World Conservation Monitoring Centre to monitor endangered species. This was an outgrowth of an earlier program by IUCN established at Cambridge, United Kingdom. In 2000, WCMC became a formal program of UNEP and has become its primary resource center for providing biodiversity information and assessments on conservation and sustainable use issues that have national, regional, and global impacts (UNEP-WCMC 2003). Its programs focus on species diversity: forests, protected areas, marine, mountain, and freshwater habitats as well as habitats affected by climate change (UNEP-WCMC 2003). Extensive use of GIS and spatial analysis helps recognize global trends, warn of potential sustainability problems, and identify priorities for conservation action in all of the earth's major ecosystems.

GIS and the Internet

With widespread development of data clearinghouses, the Internet has become a key medium for GIS data and metadata exchange. Specialized GIS user groups and organizations such as the Society for Conservation Geographic Information Systems (http://www.scgis.org) are invaluable tools. In addition to using these resources to develop their GIS, most conservation organizations develop their own Internet sites to deliver information to targeted users. This section outlines how conservation GIS users may incorporate Internet technologies into GIS programs and projects. It concludes with a look at the future direction of conservation GIS and the Internet.

One of the most important roles of the Internet in conservation GIS is to find currently available GIS data for one's area of interest. Internet search engines, such as Google (http://www.google.com) or Yahoo (http://www.yahoo.com) (mention of specific products or services in this chapter is for illustration and information only and does not reflect specific recommendations by the affiliations of the authors), can be easily used to search for desired data by keywords. This method may yield some useful results, but better success is often achieved by searching a data clearinghouse or portal (a web site that serves as a gateway to the Internet featuring a suite of services and web links for a niche topic) specifically focused on GIS data, conservation, and/or a desired region. Many GIS data clearinghouse sites exist. For example, the Geography Network (http://www.geographynetwork.com/) provides international search capabilities for GIS data sets, clearinghouses, and web applications. The National Biological Information Infrastructure (http://www.nbii.gov/) provides similar capabilities, including its own metadata clearinghouse, with a specific focus on biologic data and analysis tools. These are just 2 examples of the ever-increasing number and variety of Internet resources for finding existing GIS data.

Another major focus of using the Internet is to acquire and deliver GIS data. GIS projects typically include development of a web site to promote their project and to deliver results and data. These web sites often direct users to where the actual GIS data can be obtained, either by direct download or ordering the data. Some sites have made a business of collecting and delivering, for a fee, GIS data from a wide variety of sources. Sites that actually produce and maintain their own data often provide free GIS data. Government and nonprofit groups typically operate these free data sites. In addition to delivering GIS data, many of these sites include online mapping applications that integrate their GIS data with other data sets (visit the Geography Network for numerous links to examples). These increasingly powerful tools allow users without GIS software to perform spatial queries and produce maps in real time via the Internet.

GIS and Internet programming technologies are rapidly changing and constantly improving. Currently, GIS web applications can be divided into 2 basic types: static and dynamic. Static applications are those that provide pre-made maps, GIS data files, and statistical summaries. These applications are typically programmed with hypertext markup language (HTML or its variants) to serve maps and statistics previously created by a GIS analyst. The static application delivers data fast because the web server (the computer hosting the web application) does not have to analyze data or create the maps and statistics; it just directs the user to pre-made files. The downside is that static applications work well only for data that does not change often. Each time the GIS data changes, a GIS technician must recreate new maps and statistics, and the Internet application must be updated. The other limitations of static applications are that end-users cannot customize maps or modify data queries. They only get to view the information in the predefined formats created by the GIS technician, which may or may not be what the user needs.

To address these limitations, dynamic Internet mapping applications have become increasingly popular. A dynamic mapping application processes end-user submitted queries in real time using the GIS data sets to produce maps, statistics, and even subsets of the GIS data. A dynamic Internet mapping application can be considered as a customized online GIS, typically for non-GIS experts. This method is superior to static applications for GIS data that are continuously changing since GIS data changes are immediately reflected in the Internet application with no additional programming. The other key benefits are that users have much more flexibility in how they query the GIS data and can customize maps to better suit their needs. Users are, however, still limited to the capabilities designed into the application.

Advanced applications are beginning to focus more on spatial data analysis and manipulation instead of just data presentation. Negative aspects of dynamic mapping applications are that they are more complex and costly to implement. Programming dynamic applications typically requires more robust server programming technologies such as Active Server Pages (ASP), Common Gateway Interface (CGI), Cold Fusion, and/or Java in addition to HTML. To reduce the cost and time of application development, many organizations combine these technologies with third-party software solutions. One example is Environmental Systems Research Institute's (ESRI) ArcIMS (Internet Map Server: http://www.esri.com) that provides pre-developed, modifiable tools and templates to serve and query GIS data over the Internet (or within private intranets). Dynamic mapping applications also require higher-end servers than do static applications. Depending on an Internet site's usage and amount of data being served, multiple servers may be required for optimal performance.

Creating GIS web services is also becoming popular and should become more common in conservation organizations in the near future thanks to recent developments in programming technologies such as ASP.Net and eXtensible Markup Language (XML). Web services are applications that allow approved remote computers to query an organization's web server in predetermined ways for certain data sets. This effectively allows multiple organizations to work together and serve each other's data in different dynamic mapping applications while allowing each group to maintain its own data. Microsoft's TerraService (http://terraserver.homeadvisor.msn.com/terraservice.htm) is an excellent example of a GIS-based web service where remote programmers can incorporate U.S. Geological Survey (USGS) imagery and quadrangle maps into their Internet mapping applications without having to store these immense data sets. The Geography Network (http://www.geographynetwork.com/geoservices/) provides links to several other web services.

Another rapidly evolving technology with implications for the future of conservation GIS is mobile wireless computing. It is becoming more affordable and common to connect to the Internet via wireless phones and computers. Combining these technologies with web services allows field researchers to easily exchange data with their organization and others while in the field. For example, researchers recording bird nesting site activity could upload their findings to their organization's GIS while in the field, or they could download GIS data layers such as USGS quadrangle maps to their computer for integration with a GPS-integrated field-mapping program.

The Internet has become an invaluable resource to conservation GIS users for everything from data development to data delivery. Providing the details of implementing these technologies is impractical in this format as there are many competing technologies, each with pros and cons, and new technologies are constantly appearing that quickly supersede existing technologies. Rapid advancements in Internet server and programming technologies combined with steadily declining hardware costs are causing many conservation groups to focus efforts on dynamic mapping applications over static applications. Web services have also recently surfaced in conservation GIS and are quickly becoming widespread. These technologies, combined with those of wireless mobile computing and GPS, present new opportunities for wildlife professionals. However, through all recent changes and advances, it remains true that developing, maintaining, and delivering GIS systems, locally or via the Internet, demands high computer skill levels, knowledge of arcane macro languages, and advanced skills in computer hardware, software, and communication. More than ever, organizations can expect the need will grow to support personnel with specialized knowledge in GIS and computer hardware and software.

DATA DOCUMENTATION

Documenting information about spatial data provides developers and users with key descriptions about collection techniques, sources, process steps, and geographic details used in creating the data set. Often called metadata, this information comprises a core component of any type of spatial or attribute data. The importance of metadata lies in its ability to reduce the loss of time looking for how information was created, prevent loss of critical information, and as a safety net in case people move to other positions. As a professional, metadata provides you with the tools to record your processes and sources to use the data efficiently and effectively.

Metadata should be recorded throughout the database development process and organizations should develop operational procedures that institutionalize metadata production and maintenance. This retains valuable information about data for internal organizational or external client use, and provides a key component in sustaining a GIS program in the long term.

History of Metadata

The metadata concept was formalized at the federal level in 1994 with release of Executive Order 12906 and the Office of Management and Budget's Circular A-16 as part of a government-wide effort to reduce duplication of effort to collect information and to provide a way for other agencies and taxpayers to access data created with federal funding (Federal Register 1994). The Office of Management and Budget (2002) released a revised circular A-16 to reflect technology changes, but kept the core component of establishing a coordinated approach to electronically develop the National Spatial Data Infrastructure (NSDI). As part of the NSDI, release of the *Content Standard for Digital Geospatial Metadata* provided a common set of terms and definitions needed to document data. All types of spatial and nonspatial data can be documented using this standard. In fact, several profiles of the standard provide users with elements for biological, shoreline, or remote sensing data. Any data set created with federal funding needs documentation using this standard. Many state and local governments and other organizations that receive federal dollars have adopted the standard. Other standards exist, but many GIS professionals either use or work on data created with federal funds and need a working knowledge for their jobs.

In the next few years, the International Organization for Standardization plans to release an international geospatial metadata standard as part of an effort by a network of national standards institutes from 145 countries working in partnership with international organizations, governments, industry, and business and consumer representatives. The United States, through the Federal Geographic Data Committee, participates in this process and plans to adopt the international standard when available. Although some aspects of the standard might change, the content should remain similar and might offer some additional elements.

Box 3. Federal Geographic Data Committee metadata standard.

Sections of the Standard

1. Identification*
2. Data Quality
3. Spatial Data Organization
4. Spatial Reference
5. Entity and Attribute
6. Distribution
7. Metadata Reference*

Supporting Sections (reusable)

8. Citation
9. Time Period
10. Contact

* Denotes a mandatory section.

Overview of Content

The Federal Geographic Data Committee (FGDC) metadata standard is organized into 10 sections (7 main sections and 3 supporting sections) that provide elements to answer a series of questions (Federal Geographic Data Committee 1998, 1999, 2000).

- *Who* collected and *who* distributes the data?
- *What* is the subject, processing, projection of the data?
- *When* were the data collected?
- *Where* were the data collected?
- *Why* were the data collected (*what* is the purpose)?
- *How* were the data collected? *How* should it be used?
- *How* much does it cost?

Although the standard includes many elements, only a few require data entry while users select from a series of other elements that directly apply to their data. Many definitions provide clear descriptions about the type of information to include about the data set. However, 2 sections (2 and 5) of the standard require additional explanation to help in creation of a metadata record.

Section 2 (Data Quality) of the standard provides a general assessment of the quality of the data set.

- *Attribute accuracy report*—Assessments about the attribute values may refer to field checks, cross-referencing, statistical analyses, and parallel independent measures, etc. This does not refer to the positional accuracy of the value.
- *Logical consistency report*—These assessments relate to the fidelity of the line work, attributes and/or relationships including topological checks, arc/node structures that do not easily translate, and database QA/QC routines, such as:
  — are the values in column X always between "0" and "100,"
  — are only text values provided in column Y, and
  — for any given record, does the value in column R equal the difference between the values provided in columns R and S?
- *Completeness report*—This report identifies the data omitted from the databases that might normally be expected, as well as the reason for the exclusion including:
  — geographic exclusions (data were not available for Smith County),
  — categorical exclusions (municipalities with populations under 2,500 were not included in the study), and
  — definitions used (floating marsh was mapped as land).
- *Positional accuracy*—This is an assessment of horizontal and/or vertical positional (coordinate) values including information about digitizing (RMS error), surveying techniques, GPS triangulations, and image processing or photogrammetric methods.

Section 5 (Entity and Attribute) of the standard illustrates data content and should be a product of the data design effort. This section often might include the data dictionary, catalog of terms or some description of fields contained within nonspatial attributes.

- *Relational database format*—This is used as a *guide to record terms:*
  * entity label–table title,
  * attribute label–column titles, and
  * attribute domain values–recorded values within each column.

- *Domain types*—This includes a set of possible data values of an attribute including:
  * enumerated domain
    — a defined pick list of values,
    — categorical, such as road types, departments, tree types, etc.,
  * range domain
    — a continuum of values with a fixed minimum and maximum value, and
    — a numeric measure or count, may be alphabetic (A–ZZZ),
  * codeset domain
    — a defined set of representational values,
    — coding schemes, such as county codes or course number (GEOG 1101),
  * unrepresentable domain
    — an undefined list of values or values that cannot be prescribed, and
    — text fields, such as individual and place names.
- *Entity attribute overview*—This element provides a summary overview of the entities/attributes as outlined in either the detailed description or an existing detailed description cited in the Entity Attribute section. This field should not be used as a stand-alone general description.

Software tools provide a way to enter this information and, in many cases, automatically enter values into elements as users create their data. The FGDC provides a review of tools available for creating metadata at their website http://www.fgdc.gov.

Distributing and Accessing Metadata

A completed metadata record should be posted on the Federal Geographic Data Committee clearinghouse at www.fgdc.gov/clearinghouse/clearinghouse.html. This clearinghouse provides a single point of entry to hundreds of existing servers. Directions for organizations that want to establish a node within the clearinghouse are provided on the above web site. The clearinghouse offers access to a wealth of metadata to help discover potential data sets of interest as well as examples to use when creating records.

The website www.fgdc.gov offers a wide range of tools, training, and information about creating and serving metadata and provides links to a variety of agencies and organizations that specialize in metadata.

Box 4. Recommendations for writing metadata (Federal Geographic Data Committee 2000).

- Use Clear, Familiar Words
- Use an Informative Title
- Select Keywords Wisely
- Write Complete Sentences
- Use Bulleted Lists
- Ask Someone to Review Metadata
- Define and Describe Acronyms, Jargon or Technical Terms

USING GLOBAL POSITIONING SYSTEMS

In recording wildlife information, a fundamental component is location. Thus, it is important to understand the Global Positioning System (GPS) and how it can be used. There are several self-help guides (Letham 1998, Anderson 2002) if one desires a more in-depth understanding. This system helps land, sea, and airborne users locate where they are on earth 24 hours a day by triangulation of earth orbiting satellites; typically 3 satellites are needed to obtain a triangulation. The GPS unit is actually a receiver that measures distance using travel time of radio signals; this signal must be corrected for any delays that it experiences as it travels through the atmosphere.

So how does GPS work? It all relates to the *velocity* that a satellite signal travels versus the *time* it takes the signal to travel; in GPS the velocity is equal to the speed of light or roughly 299,338 km (186,000 miles) per second. The principal problem comes from measuring the travel time. That is, GPS uses Pseudo Random Code, which is a digital code that contains a complicated sequence of "on" and "off" pulses. The signal appears to be random electric noise, however, in actuality the noise is a series of complex patterns to help ensure that receivers do not synchronize to another signal. Because each satellite has its own unique codes, the complexity also assures the receiver will not pick up a signal from another satellite. Thus, all satellites can use the same frequency without jamming one another.

Distance to a satellite is calculated by measuring how long a radio signal takes to reach a receiver. To make this measurement, we assume that both the satellite and our receiver are generating the same random codes at exactly the same time. By comparing the time of the satellite versus our receiver, we can calculate how long it took for the signal to reach us. The travel time is then multiplied by the speed of light to get the distance. However, identifying the exact time is the crucial element in making this calculation.

Satellites used for GPS have atomic clocks, but GPS receivers do not. So how are the clocks synchronized so the calculation can be made? Although 3 satellites can locate a point in 3-dimensional space, a fourth satellite is needed to identify the time (Fig. 6). The premise is to have all 4 satellite signals intersect a single point. Because the

Box 5. GPS satellites.

Navstar GPS was developed by the Department of Defense and manufactured by Rockwell International. These 24 satellites are placed in 6 orbital planes at 10,900 nautical miles or 20,200 km above the earth. Each plane is inclined 55 degrees relative to the equator. Satellites weigh about 710 kg and are 5.2 m wide with solar panels extended. Their orbital period is about 12 hours and they pass over one of the ground stations twice a day. The lifespan of these satellites is planned at 7.5 years. Using 4 or more satellites can yield 3-dimensional estimates while using 3 satellites can only generate 2-diminsional observations.

Fig. 6. Three satellites are used for triangulation while a fourth satellite takes another measurement to check the other 3.

receiver's clock is not as accurate as the satellite's, the fourth signal would not intersect the first 3 satellite's triangulation, so a discrepancy in the fourth measurement occurs. Since any offset of time can affect all of the measurements, the receiver corrects the discrepancy by calculating a factor that can be subtracted from all measurements of time so that all measurements would intersect at one point. Once it has the correction factor, it is applied to all measurements. Thus, any GPS receiver where a precise position is desired will require 4 channels so that it can make 4 measurements simultaneously. But for triangulation to work, one also needs to know where the satellites are in space. The Department of Defense has placed each satellite in a precise orbit in accordance to their GPS Master Plan. Because of their precise orbits, each satellite passes over a ground station twice a day, which affords an opportunity to measure its altitude, position, and speed. Any corrections, called *ephemeris errors*, are sent back to the satellite. The satellite then transmits corrections with its timing information. Thus, each GPS receiver is relayed exact orbital information. To further enhance the location of the satellite, each GPS receiver can obtain an "almanac" from any one of the satellites, which tells where in the sky it should be at any given time. The GPS receiver uses the almanac and transmission corrections to precisely establish each satellite's location.

Because satellite signals are transmitted through space, they are susceptible to degradation and delays. The atmosphere causes some delays while others can come from multi-path effects resulting from the transmitted signal bouncing off another object before getting to the receiver. A quick way to handle atmosphere-induced errors is to compare the relative speeds of 2 different signals. This is called, dual frequency measurement; it is complex and can only be found as a feature on advanced GPS receivers. The ultimate accuracy of GPS is calculated from multiple sources of error, and the process to correct most of the source errors from a satellite clock, orbit, ionosphere, or troposphere is known as *Differential Correction.*

Box 6. Ground stations.

Known as the "Control Segment," these stations monitor each satellite's health and exact position in space. They correct *empheris errors* such as clock offsets and transmit corrections to the satellites. There are 5 stations worldwide, Hawaii and Kwajalein in the Pacific Ocean, Diego Garcia in the Indian Ocean, Ascension Island in the Atlantic Ocean, and Colorado Springs, Colorado, USA, which is the master ground station.

The military maintains the most precise system (dedicated for military operations) and began in March 1990 to degrade the performance accuracy for commercial or nonmilitary applications by an approach called selective availability. Selective availability essentially involved modifying the clock frequency to randomly degrade the accuracy of commercial performance to about 100 m. In May 2002, the Clinton Administration had the Defense Department stop using selective availability so that a greater accuracy (1–10 m) could be obtained for commercial or nonmilitary uses.

Differential Correction for GPS

Differential GPS involves 2 receivers that are in relatively close proximity (typically within ~200 km); one is stationary and the other is roving and recording data. Because of this close proximity, in comparison to the distance of satellite transmission travel, signals that reach both receivers will have traveled through virtually the same atmospheric conditions and will have the same errors. To correct these errors, the receiver that has a fixed known location brings all satellite information into a local point of reference. This information is compared to the data transmitted from the satellite(s) and corrected. The corrected information is then used in conjunction with data collected by the roving field receiver(s). Because one of the receivers has a known surveyed location, it uses this information to compare what the GPS signals should be versus what they recorded. The difference is the error correction factor provided to the other roving receivers. Since the fixed receiver has no way of knowing which satellites the roving receivers are using, the reference receiver computes error correction factors for each satellite signal it can distinguish. When correcting errors associated with GPS, it can be done while the points are being collected, a process known as real-time *Differential Correction* or, after collection of points, known as *Post-Processing.*

In the early days of GPS, reference stations were established and maintained by private companies. One would then have to buy data from a reference receiver and establish a communication link to a field receiver. Because of the demand by public agencies to use GPS, this reference information is now accessible at no cost. For example, the U.S. Coast Guard has navigation beacon placements throughout the United States; this information can be found at the Coast Guard's web site at www.navcen.uscg.gov/dgps/coverage/Default.htm. More can be learned about Differential GPS from the Starlink website, www.starlinkdgps.com/dgpsexp.htm.

Wide Area Augmentation System

Because of the ability of GPS to fix an airplane's location in real-time, the Federal Aviation Agency (FAA) has developed the Wide Area Augmentation System (WAAS) that extends coverage for differential GPS to the entire United States. WAAS is a critical component of the FAA's strategic objective of a seamless satellite navigation system for civil aviation. This system improves the accuracy, availability, and integrity of GPS, thus, improving its' capacity and safety. Ultimately, WAAS allows GPS to be used as a primary means of navigation from takeoff through Category 1 precision approach (i.e., close to the runway but not zero visibility; Category 3 landings are zero visibility). The ramifications of the FAA maintaining this system go well beyond aviation; because of its design the system helps ensure that differential GPS corrections will be accessible to all who need them. The Garmin website at www.garmin.com/aboutGPS/waas.html further discusses WAAS.

Using GPS

There are 2 main questions to be answered in using GPS to help identify your needs: what is your main purpose—do you need a GPS receiver of mapping or survey grade, and what level of accuracy is required—do you need to use differential GPS techniques for accuracy of 1m or less? Thus, to help set up the GPS unit, you need to be familiar with some data capturing and processing terms (Boxes 7, 8, 9).

GPS Uses in Wildlife

What are the practical applications for using GPS in the field for wildlife biologists and managers? Presently, there are 2 common areas of use: 1) tracking and recording wildlife movements, and 2) inventorying, mapping, and/or surveying wildlife habitats or specific wildlife use areas. Using a GPS tracking collar can aid in recording wildlife movements (Fig. 7) and provide more accuracy than other tracking systems (Rempel and Rodgers 1997). Since 1994 a number of GPS collars have been developed using the Navstar Global Positioning System. GPS collars have been used to successfully track large mammals such as moose (*Alces alces*) (Rodgers et al. 1997), grizzly bears (*Ursus arctos*) (Waller and Servheen 1999), caribou (*Rangifer tarandus*) (Dyer 1999), mountain lions (*Puma concolor*) (Bleich et al. 2000) and gray wolves (Merrill and Mech 2000).

These collars now come in different sizes and can be used on small, midsize, or large mammals. Collar weight varies from 100 to 2,100 g (depending on collar size), and can store up to 10,000 locations (nondifferentially corrected or 5,000 locations differentially corrected) depending on recording frequency and battery configuration. They operate in temperatures ranging from –30 to +50 C, and the data can be retained in the collar at temperatures ranging from –50 to +75 C. Collars can be configured to allow periodic data downloads, or all the data can be transferred

Box 7. Receivers.

GPS receivers can be carried by hand or installed in airplanes, boats, cars, or trucks. These receivers detect, decode, and process GPS satellite signals. The typical hand-held receiver is about the size of a cellular phone or palm computer, and they are getting smaller all the time.

Box 8. Definitions of terms for data capturing standards.

- Static Mode—These are points collected at 1-second intervals; a general guideline is to collect point positions at one-second intervals. The amount of data collected varies with the type of receiver.
- Kinematic Mode—The time between measurements will vary depending on velocity at which data are collected. Measurement interval will usually not exceed 1 second; these data are stored in the receiver for later downloading and post-processing.
- Signal to Noise Ratio (SNR)—The SNR of a signal is a measure of its quality at the GPS receiver. The higher the value, the stronger the desired signal is compared with associated noise. A low value would indicate a weaker signal, and/or higher levels of noise; for example, a setting of 6 might be used.
- Elevation Mask—This ensures the rover (field) receiver is using the same set of satellites as the base station. For a distance of <500 km to the base station, 15° should be used while 20° should be used for a distance of <1,000 km.
- Satellite Vehicles—This is the minimum number of satellites required to record a position, usually 4 or more.
- Datum—This is a smooth mathematical surface that closely fits the mean sea-level surface, for example NAD83.
- Spheroid—This is a spheroid of 'best fit' over the surface of the earth, for example GRS1980.
- Positional Dilution of Precision (PDOP)—This is an indication of the quality of the results that can be expected from a GPS point position. These values should be used as an indication of when GPS is likely not to produce good positioning results and, equally, should not be used as a measure that describes the quality of positioning that has actually taken place; a typical setting would be less than 6.0.
- Base Station—This is a stationary receiver at a known location that provides the data used in the differential corrections of GPS data acquired by a moving receiver; a rover (field) receiver should be within <500 km of the base station when using differential corrections.

Box 9. Differential processing standards.

- Data Format—The user must acquire the base station data in a format compatible with the software they will use for differential correction, for example, ArcView® shapefile or ArcInfo® coverage.
- Unit of Measurement—One foot equals 0.3048 m exactly.
- Coordinate System—Data are typically collected in longitude and latitude coordinates, however, these can be converted to State Plane, Universal Transverse Mercators (UTM) or others.
- Elevation Mode—NGVD 29 (47).
- An approved Base Station—An example for western Oregon is Corvallis, CORS ARP.

to a computer when the collar is retrieved. A source of concern, however, in using GPS collars lies with locating an animal such as elk in a forest of varying density and topography. Rumble and Lindzey (1997) found that nearly 50% of attempted GPS locations failed in stands with >70% overstory canopy cover; in stands with less canopy failure of GPS location attempts was lower. Attempts to model the effects suggested a positive linear relationship ($P \leq 0.01$) between failure of GPS location attempts and tree density, tree basal area, and an index of diameter at breast-height times tree density. Gamo et al. (2000) noted that vegetation could block signals from satellites to GPS radio collars while Dussault et al. (1999) cited vegetation as well as steep terrain and weather as affecting receipt of GPS signals. However, B. K. Johnson of the Oregon Department of Fish and Wildlife (personal communication) indicated that because of recent technology advancements, their recent evaluation of GPS collars demonstrated much better than 60% signal receipt in stands with >70% overstory canopy closure.

GPS technology can also be used to inventory, map, and monitor marine, fish, and wildlife habitats. For instance, GPS has been used to delineate coral reefs (Field et al. 2000), terrestrial wildlife habitats (Kiilsgaard 1999, O'Neil and Barrett 2001), and fish habitats (Martischange 1993, Threloff 1993, Waddle et al. 1997). GPS is also a navigation tool (Anderson 2002) that allows researchers to accurately track their movements and guide themselves to an exact location, such as a coral reef, and then record the delineation of the reefs. Development of wildlife habitat maps requires interfacing GPS with a map database that allows one to store information on the map. This requires the ability to create a moving map, which occurs when the GPS receiver takes the information and displays its current position on the map and, as one moves, the map also moves. Thus, one can be assured of their locations and the location of what they are classifying. Currently, GPS can be directly linked to laptop computers. GPS typically communicates to the computer by using a standard linking mode, NMEAD 183 GGA GSV. Magellan and Trimble have their own standards in which they communicate with a laptop and some are proprietary to a specific GPS model. Also, there are several software programs that interface with GPS to allow on screen recording of information, such as Fieldnotes 32 GPS by Penmetrics (Corvallis, Oregon), SOLO CE by Tripod Data Systems (Portland, Oregon), and ArcPad by ESRI (Redlands, California). In each program, the primary function is to collect positions, attribute these data, as well as locate existing points in the field.

In the future, GPS units will become smaller and the technology will become more wide spread for non-commercial uses. We can also expect GPS to work more effectively with satellites like ARGOS where GPS data is periodically linked to a satellite and then downloaded at a later time by the user. The main factors critical to continuing the development of this tool for wildlife work are: size, power consumption, and reliability. Advances in these areas will help assure that GPS may someday be used on small animals. *GPS World Magazine* (www.gpsworld.com), *Telonics Quarterly* (www.telonics.com), or

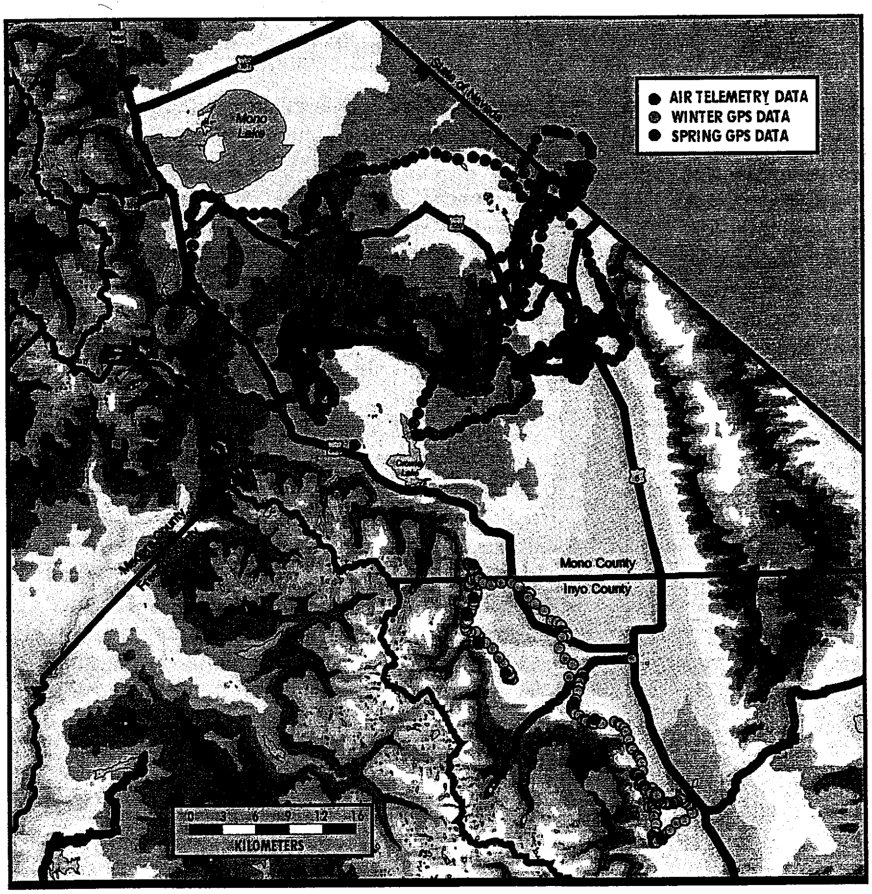


Fig. 7. Mountain lion locations during winter and spring as recorded from a GPS collar (Bleich et al. 2000).

GeoCommunity (www.geocomm.com) bring together a great amount of information about the current state of GPS and GeoSpatial technology issues and their applications. Navtech's site, www.navtechgps.com/glossary.asp, presents a link to a GPS Glossary of Terms. Finally, with more and more people using GPS, resource managers will face new problems. One challenge will come with linking GPS to fish echo sounders that will allow people to find and exploit a resource faster than previous methods (Fisheries Western Australia 2000). Thus, technology can help us learn more about a resource or species, as well as cause its accelerated decline, if we do not use it wisely.

USING REMOTELY SENSED DATA

Digital Image Processing

To be effective in management decisions, maps and GISs require timely and accurate information. Remote sensing and digital image processing have the potential to meet these needs as well. In the near future, there will be an unprecedented availability of digital data from satellite sensors in response to concerns about human impacts on the earth, habitat monitoring, and global climate change (Ormsby and Soffen 1989, Justice et al. 2002). However, Graetz (1990) believed that currently available remote sensing technology far exceeds the scientific capability of interpreting and applying it. If remote sensing data are to be used to their fullest potential, the challenge will be to develop realistic spectral, spatial, and temporal processes for extracting information from the images. Several excellent books describe remote sensing and digital image processing (Swain and Davis 1978, Estes et al. 1983, Schowengerdt 1983, Curran 1985, Richards 1986, Campbell 2002).

Digital image processing, the numerical manipulation of digital images, includes procedures for pre-processing, enhancement, and information extraction. Pre-processing involves procedures applied to the original data before enhancement or information extraction. Calibration of image radiometry for atmospheric conditions, illumination and view geometry, correction of geometric distortions, georegistration of the image, and noise suppression are examples of image pre-processing procedures (Schowengerdt 1983).

Image enhancement involves application of procedures designed to facilitate the interpretation of images. These procedures include contrast and color manipulations and spatial-filtering methods (Schowengerdt 1983). The "Tasseled Cap" is a well-known spectral transformation, which derives new variables that allow vegetation and soils information to be extracted, displayed, and understood more easily (Crist et al. 1986). Hodgson et al. (1988) used this transformation with Landsat TM (Thematic Mapper) data to study wood stork (*Mycteria americana*) foraging habitat. Jackson (1983) provided a general procedure to develop spectral indices for user-defined features in a scene.

Development of processes for extracting information from remotely sensed data requires an understanding of the image-forming process. Strahler et al. (1986) provided a framework for identifying appropriate procedures given characteristics of the image and the scene. The most common information-extraction methods used with remote sensing data are spectral classifiers in which each pixel is processed independently of its neighbors or location in the image. This process is appropriate when scene objects are larger than the spatial resolution of the sensor.

The process to automate extraction of information from the imagery, spectral classification, can be generalized as being supervised or unsupervised (Swain and Davis 1978, Schowengerdt 1983). In supervised classification, a sample of image elements for each land cover class is used to estimate parameters, typically a mean vector and covariance matrix, to derive land cover for the entire scene. In unsupervised training, a clustering algorithm is used to partition a sample of the data into populations of pixels with similar reflectance. These are referred to as spectral classes for which parameters can be estimated (Richards and Kelly 1984). In unsupervised training, the analyst attempts to establish correspondence among the spectral classes and land cover classes. A statistics file consisting of a mean vector and covariance matrix for each land cover class is used in a classification algorithm to derive land cover for the entire scene. The product from a maximum likelihood classification, a common method that produces results having the minimum probability of error over the entire set of data classified, is an image in which each pixel is assigned the label of the land cover class for which the *a posteriori* probability was the maximum (Fig. 8).

Digital image processing techniques can also be used when the scene objects are smaller than the resolution element of the sensor. A relationship between the reflectance and a property of a scene, such as canopy cover, is established and used to estimate the property in each pixel in a continuous fashion (Fig. 9). Mixture models are used when the objective is to estimate the proportions of scene objects in each pixel. Mixture models have been used for a variety of resource inventories, including waterfowl habitat (Work and Gilmer 1976), rangeland vegetation and soil cover (Pech et al. 1986), and wintering geese (Strong et al. 1991).

Spectral-spatial scene models exploit the spatial structure of images as well as their spectral characteristics to infer properties and processes at the land surface. Several spectral-spatial models are available. Some scene models segment the image into contiguous groups of pixels that meet a spectral similarity criterion and perform the classification using all pixels of the feature (Strahler et al. 1986) (Fig. 10). Other spectral-spatial models exploit a measure of image texture or the spatial autocorrelation function as an additional feature in the classification process (Shih and Schowengerdt 1983, Pickup and Chewings 1988).

Spectral-temporal models use the change in the spectral properties of images acquired at different times to infer properties or processes at the land surface. The "Tasseled Cap" is an example of a spectral-temporal model of phenological development of agricultural crops that can be used to identify crops and forecast yields (Kauth and Thomas 1976, Wiegand et al. 1986). Time series of the normalized difference vegetation index, calculated from the red and infrared spectral reflectance measurements of the Advanced Very High Resolution Radiometer sensor, have been used to describe and map intra- and inter-year phenological dynamics of biomes at regional, continental, and global scales (Justice et al. 1985), infer net primary productivity (Goward et al. 1985), and measure dynamics of vegetation at transition zones between biomes (Tucker et

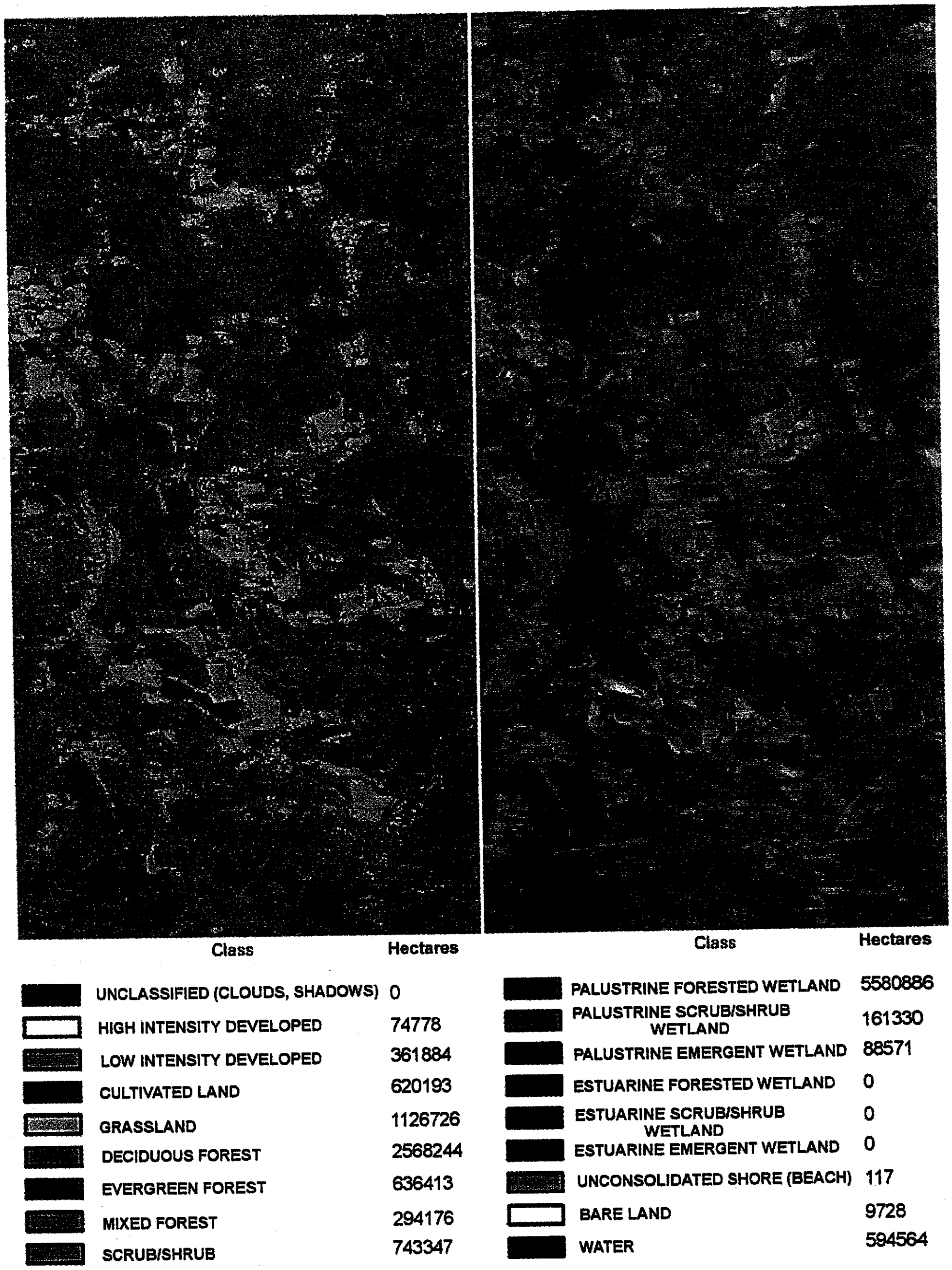


Fig. 8. Land cover information derived using an unsupervised classification approach from a Landsat image. Land cover is shown on the left and the Landsat image; bands 4, 5, and 3 displayed in red, green, and blue; is shown on the right.

al. 1991). Techniques for detecting change (Singh 1989) use images acquired at different times to infer changes in land cover. Koeln and Bissonette (2000) used "Cross Correlation Analysis" to delineate areas of wetland changes as derived from Landsat imagery (Fig. 11).

The flow of information between remote sensing and GIS should not be one-way. Accuracy of information derived from remote sensing can benefit from access to accurate spatial data within a GIS. Integration of the parallel technologies of GIS and remote sensing will be important to full maturation of both areas.

Remote Sensing of Habitat: Landsat Imagery

Remote sensing has been used in wildlife biology for many years. Historically, small format aerial photographs were the most commonly used method of remote sensing used for mapping habitats. As habitat mapping requirements expanded, use of large format photography from 9 × 9 "inch" metric mapping cameras became more common. The cost of acquiring large format photography and manual interpretation of aerial photographs was high and often prohibitive. Satellite imagery was frequently used to replace or augment use of aerial photography for habitat mapping, primarily to reduce cost. Since the 1970s satellite imagery (primarily Landsat imagery) has been used to map wildlife habitat (Work and Gilmer 1976). In the 1970s the cost of computer systems required to process digital imagery limited using Landsat imagery for habitat mapping. With improvements in software and hardware, and reduction in costs, remote sensing is a frequently used

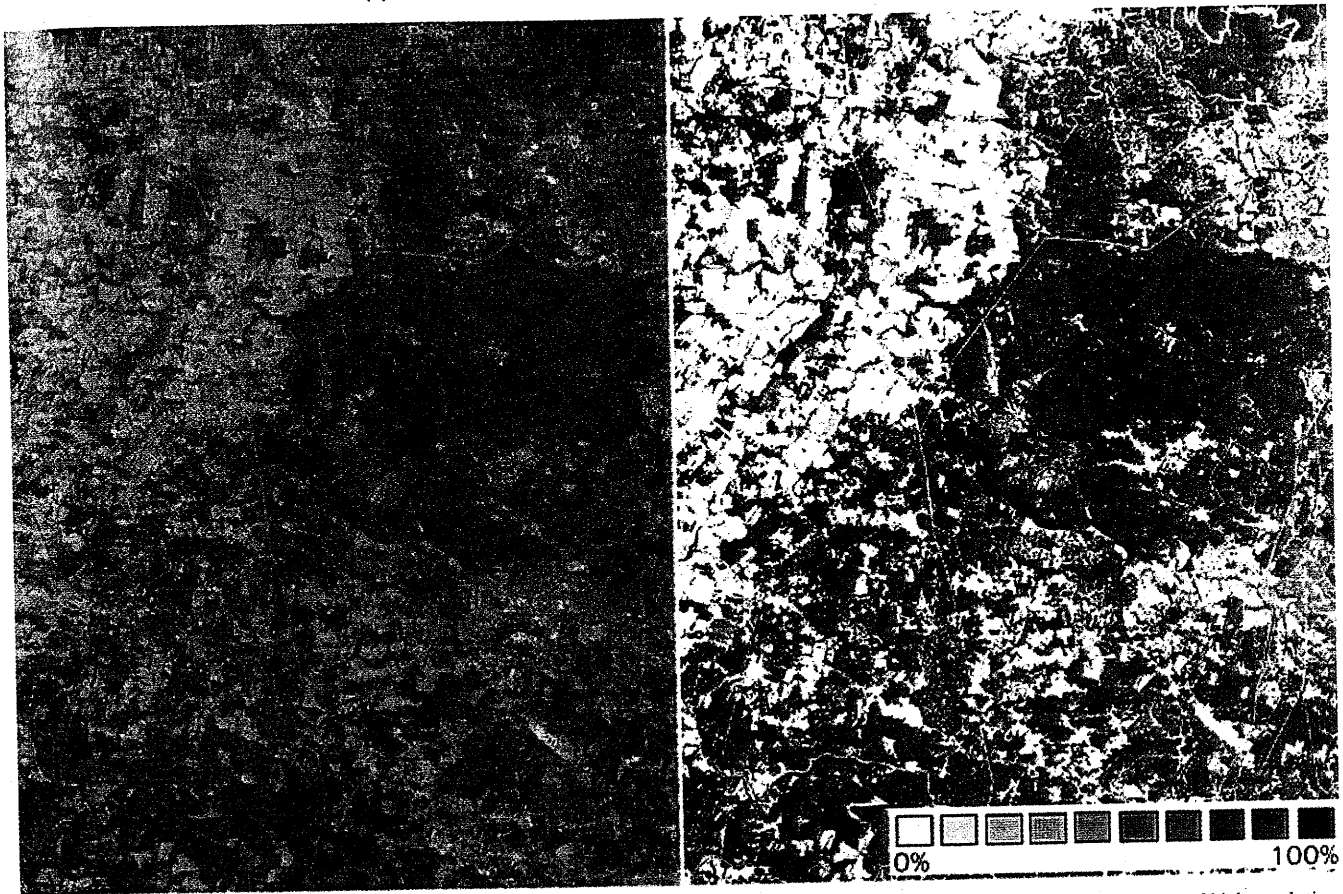


Fig. 9. Percent tree canopy cover (right), ranging from 0 in white to 100% in dark green, calculated using CART technology: samples of high-resolution imagery, and the Landsat image (left).

Fig. 10. Digital image processing algorithms are available for image segmentation and may improve the process of mapping wildlife habitats from digital imagery. A portion of a Landsat image is displayed at the left while the image segments (red polygons) that were delineated in a fully automated process are displayed at right.

tool for mapping habitats, particularly over large regions (watersheds and states). Ducks Unlimited, working with the National Aeronautics and Space Administration (NASA) in the early 1980s was an early pioneer in use of Landsat imagery to map waterfowl habitat (Koeln et al. 1988). Today, many conservation organizations, state wildlife agencies, and resource management organizations such as the U.S. Fish and Wildlife Service, U.S. Forest Service, and the Bureau of Land Management use Landsat imagery for mapping and monitoring habitat. Since the early 1980s, Landsat imagery has been used in the management of many species of wildlife. Palmeirim (1985) used Landsat imagery to identify potential release sites for reintroduction of ruffed grouse in Kansas. Hepinstall and Sader (1997) used Landsat imagery and breeding bird survey data to model the probability of bird species occurring within areas of Maine. Landsat imagery is widely used in the National Biodiversity GAP Analysis Project (Scott et al. 1993, Lillesand et al. 1998, Kiilsgaard 1999, Kiilsgaard and Barrett 2000).

History of Landsat

On 23 July 1972, NASA launched the first in a series of satellites designed to provide repetitive global coverage of the earth's landmasses. It was designated initially as the Earth Resources Technology Satellite-A (ERTS-A). The second in this series of earth resources satellites (designated ERTS-B) was launched 22 January 1975. It was renamed Landsat 2 by NASA, which also renamed ERTS-1 to Landsat 1. Additional Landsat satellites were launched in 1978, 1982, 1984, and 1999 (Landsats 3, 4, 5, and 7, respectively). Landsat 6 was launched on 5 October 1993, but failed to achieve orbit. Each successive satellite system had improved sensor and communications capabilities.

Landsat 1, 2, and 3 had 2 earth-imaging systems, the return beam vidicon (RBV) and the multispectral scanner (MSS). The RBV system generated high-resolution television-like images of the earth's surface. RBV cameras in Landsat 1, 2, and 3 were designed to be the primary imaging systems on Landsat. However, technical problems on all 3 systems precluded routine acquisition of high-quality images from the RBV cameras. The MSS systems were much more successful and became the primary sensors on Landsat.

The RBV cameras were not continued on Landsat 4. In addition to the MSS system, Landsat 4 and 5 also contained the Thematic Mapper (TM) sensor, which provided significant improvement to remote sensing. The TM sensor records 7 bands of information for each pixel in blue-green, green, red, near infrared, 2 wavelengths of mid-infrared, and far infrared spectral regions. Routine collection of MSS data by Landsat 5 was terminated in late 1992.

The Enhanced Thematic Mapper Plus (ETM+) sensor on Landsat 7 (launched on 15 April 1999) is the most advanced of the Landsat sensors. ETM+ replicates the capabilities of the TM instruments on Landsats 4 and 5. It includes new features that make it a more versatile and efficient instrument for global change studies, land cover monitoring, and large area mapping than previous sensors in the Landsat series. These features include:

- a panchromatic band with 15 m spatial resolution,
- a thermal infrared band with 60 m spatial resolution,
- improved radiometric calibration,
- on-board, solid state recording device, and
- improved spatial geometry (improved positional accuracy).

Landsat Characterization

Landsat satellites orbit in a polar (north to south path), sun-synchronous orbit at a nominal altitude of 920 km above earth for Landsats 1-3 and 705 km above earth for Landsats 4, 5, and 7. A sun-synchronous orbit ensures the satellite passes over the earth at the same local sun time so that sun illumination conditions are consistent. Although sun elevation, relative position, and intensity still vary with seasons, each Landsat scene has the illumination of the same time of day. The Landsat 4, 5, and 7 orbit has an equatorial crossing time of 0945 hours and a return period of 16 days (i.e., every 16 days the orbit path would repeat itself). Landsats 1-3 had a return period of 18 days. Each image collects data for an area approximately 185 km east-west and 170 km north-south (for example Fig. 12 presents a full Landsat scene centered over Washington, D.C., USA). Scene locations are identified by path and row; Landsats 4, 5, and 7, require 233 paths to cover the entire earth and each path is divided into 119 rows.

The characteristics of the MSS bands were selected to maximize their capabilities for detecting and monitoring different types of earth's resources. For example, MSS band 1 can be used to detect green reflectance from healthy vegetation, and band 2 was designed for detecting chlorophyll absorption in vegetation. MSS bands 3 and 4 were ideal for recording near-infrared reflectance peaks in healthy green vegetation and for detecting water-land interfaces.

The thematic mapper (TM) is an advanced, multispectral scanning, earth resources sensor designed to achieve higher image resolution, sharper spectral separation, improved geometric fidelity, and greater radiometric accuracy and resolution than the MSS sensor. TM band 1 can penetrate water for bathymetric (water depth) mapping along coastal areas, and is useful for soil-vegetation differentiation and for distinguishing forest types. TM band 2 can detect green reflectance from healthy vegetation, and band 3 is designed for detecting chlorophyll absorption in vegetation. TM band 4 is ideal for near-infrared reflectance peaks in healthy green vegetation and for detecting water-land interfaces. The 2 mid-infrared bands on TM are useful for vegetation and soil moisture studies, and are capable of discriminating between rock and mineral types. The far-infrared band on TM is designed to assist in thermal mapping, and for soil moisture and vegetation studies. All 9 bands (8 spectral ranges) of the ETM+ sensor for a portion of a Landsat scene have specialized uses (Fig 13).

The MSS data have a pixel resolution of 79×57 m. For bands 1-5 and 7 of Landsats 4 and 5, the TM data have a pixel resolution of 30 m and for band 6 (the thermal band), the pixel resolution is 120 m. For the ETM+ sensor on Landsat 7, bands 1-5 and 7 have a pixel resolution of 30 m; band 6 (the thermal band) has a pixel resolution of 60 m, and band 8, the panchromatic band, has a pixel resolution of 15 m.

Obtaining Landsat Imagery

The Landsat Program is a joint initiative of the U.S. Geological Survey (USGS) and NASA. NASA has been

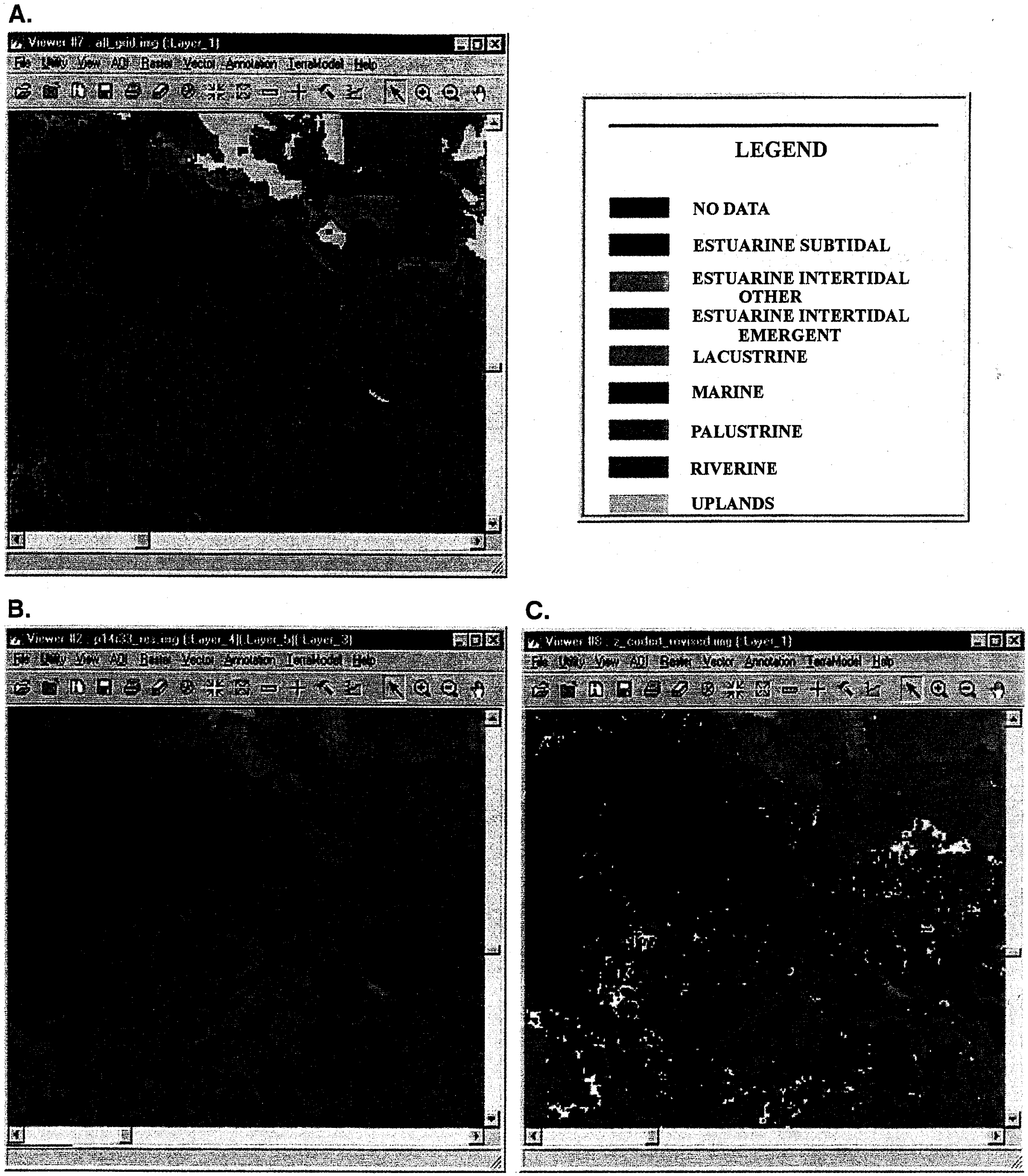


Fig. 11. Cross Correlation Analysis (CCA) can be used to detect changes between 2 images of different dates or an existing map and an image. A, illustrates a portion of a National Wetlands Inventory map with the associated legend. B, illustrates a small portion of a Landsat image used to identify changes in wetlands. The areas shown in red, green, and yellow (C) are the results from CCA and show areas of wetland losses.

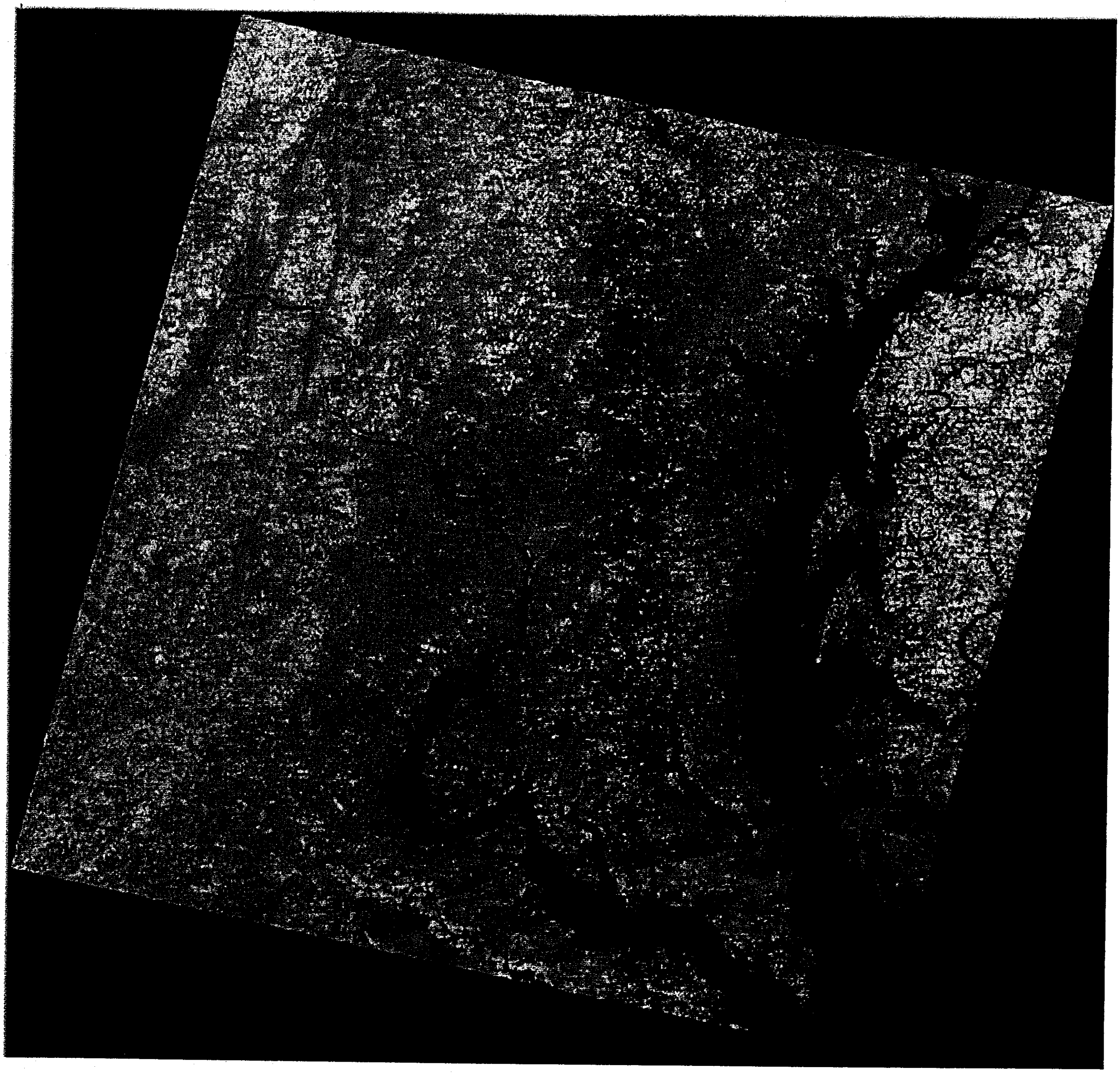


Fig. 12. A Landsat 7 Enhanced Thematic Mapper Plus scene.

responsible for developing and launching spacecraft, while the USGS is responsible for flight operations, maintenance, and management of all ground data reception, processing, archiving, product generation, and distribution. The primary receiving station is the EROS Data Center (EDC) in Sioux Falls, South Dakota. Daily, over 250 Landsat 7 scenes are downloaded to EDC. Some of these scenes covering parts of North America are acquired by direct real-time downlink. Scenes taken in other parts of the world are recorded using the on-board, solid-state, recording device and then downloaded to EDC as Landsat 7 orbits overhead. In addition, there are international ground stations receiving Landsat images in Argentina, Australia, Brazil, Canada, China, Europe, Indonesia, Japan, South Africa, and Thailand.

Users of Landsat imagery can obtain the imagery from EDC or from any of the international ground stations. EDC offers an efficient browse tool to preview and order Landsat imagery (http://edcsns17.cr.usgs.gov/EarthExplorer/). Through this interactive tool, one can select the type of image, spatial coverage required (by geographic coordinates, place name, or path/row), acquisition date, and other requirements. The results of the search are immediately provided and the user can preview any of the scenes and order those that best meet their requirements. Each Landsat scene ordered costs $600.00 ($480.00 per scene when ordering 25 or more scenes) (year 2003 costs) and can be placed on the file transfer protocol (FTP) site for downloading by the purchaser or can be shipped to the purchaser on CD-ROM.

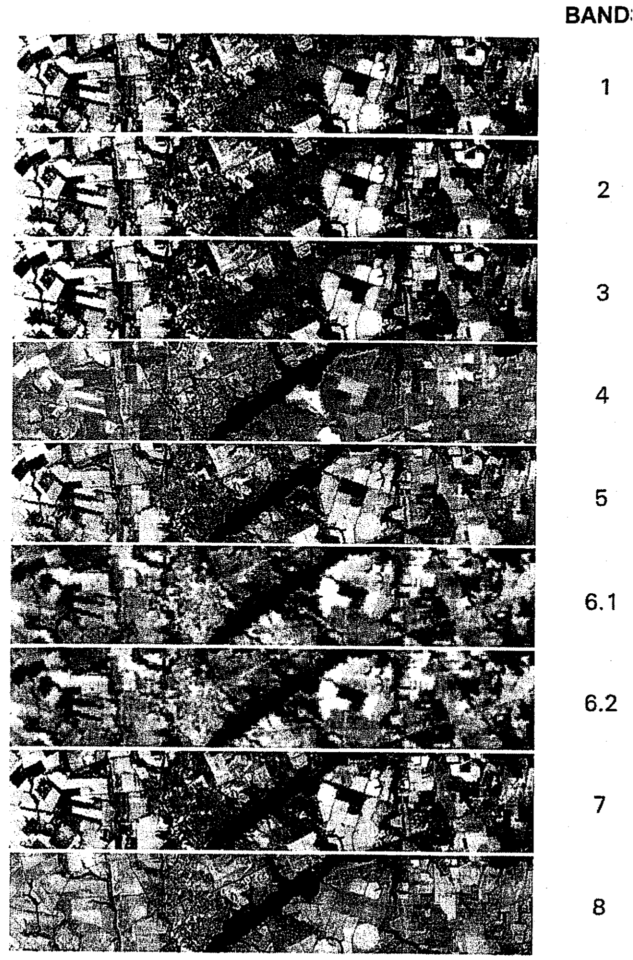


Fig. 13. The Enhanced Thematic Mapper Plus sensor on Landsat 7 collects imagery in 8 spectral ranges.

Other Sources of Landsat Imagery

Scenes obtained from EROS Data Center are typically not registered precisely to a map base. The process of registering an image to a map base is referred to as orthorectification. Most applications of Landsat imagery require orthorectification to allow the user to obtain precise coordinates of the features extracted from the image. Sponsored under NASA's Scientific Data Buy program, the GeoCover™-Ortho program has created a geodetically accurate digital database of Landsat TM and MSS multispectral imagery covering the earth's land mass and is in the process of creating a global digital database of Landsat ETM+ imagery. Earth Satellite Corporation (EarthSat) of Rockville, Maryland was contracted by NASA to obtain the best available Landsat images from the 1980's, 1990's, and 2000's and to orthorectify and spatially co-register these images. These images are available from USGS and can readily be used for habitat mapping and mapping habitat change over time.

COVER CLASS	A	B	C	D	E	
A	2		1			
B	7	10	3		2	
C	1		6	1		
D				9		
E					8	
						DIAGONAL TOTAL = 35

Fig. 14. Error matrix for hypothetical accuracy assessment data. Data are presented for 5 cover classifications (A, B, C, D, E) sampled 10 times each with possible classification errors. The diagonal total is the number of correctly classified covers: overall accuracy is diagonal total divided by total sampled points, 35/50 = 0.7 or 70% accuracy. Individual cover class accuracies can be calculated via diagonal total divided by column total (producer's accuracy) (e.g., cover class A has a producer's accuracy = 2/10 = 0.2 or 20% producer's accuracy). User's accuracy is diagonal total divided by row total (cover class A has a user's accuracy = 2/3 = 0.66 or 66% user's accuracy).

The GeoCover™-Ortho coverage is comprised of over 21,000 Landsat images that have been photogrammetrically adjusted and digitally orthorectified to create a seamless global coverage of multispectral digital imagery with 50-m root mean square error (RMSE, a measure of the geodetic positional accuracy of the imagery). The Landsat source images have been hand picked from the Landsat archives of the EROS Data Center and international ground stations, and represent the highest image quality and lowest cloud cover available for the specified time period. GeoCover™-Ortho provides readily available, affordable, and accurate Landsat MSS imagery from the early 1980's, Landsat TM imagery from the early 1990's, and Landsat ETM+ imagery from the early 2000's. This imagery can be used as a geodetically accurate base map and also provides an excellent digital source for multispectral image processing and analysis. These images provide an excellent source of data to monitor habitat changes in 10-year increments over 20 years. These images can be obtained from EDC for $65.00 per scene (year 2003 costs). Working initially with NASA and currently with the National Imagery and Mapping Agency (NIMA), EarthSat has developed a set of procedures and processes to produce a land cover analysis for all land areas of the world using Landsat TM and ETM+ data rectified under the GeoCover™-Ortho program.

Landsat imagery provides an excellent tool for mapping and analyzing changes that have occurred in the landscape. It provides an economical tool (<$0.02/km^2) that has historically been underused by natural resources managers. With reduction in the cost of imagery, and improvements and reduction in costs of computers and image processing software, Landsat imagery will be used more frequently in the future. Landsat imagery has historically been used more than any other source of satellite imagery for habitat mapping. However, Landsat imagery is not the only available source satellite imagery for habitat mapping. Other sensors, AVHRR, MODIS, SPOT, HYPERION, RADARSAT, ASTER, ALI, IKONOS, and QuickBird provide imagery ranging in spatial resolution from 0.6 to 1,000 m, and are readily available for mapping and monitoring natural resources.

Remote Sensing of Animals: Forward-looking Infrared (FLIR)

Aerial census is often the only practical way to estimate wildlife numbers (Remington and Welsh 1989) because of access, response of the animals to ground observers, or size of the study area. An infrared (IR) sensor mounted on an aircraft can increase detection rates of animals at a lower cost than using human observers.

Visibility is the most important factor affecting population estimates (Pollack and Kendall 1987, Samuel et al. 1992, Bodie et al. 1995). A human observer may be able to differentiate perhaps 20 shades of gray (Wyatt et al. 1985), while an 8-bit computer processor can provide 256 shades of gray allowing additional detection capabilities. Infrared is emitted energy while human vision uses reflected energy. Thus, infrared does not require movement, large groups, or contrast (e.g., animals on snow). Aerial surveys using human observers have limitations because biases may occur as a result of observers (Simmons and Hansen 1980), technical problem (Caughley 1974), or more commonly, visibility (Remington and Welsh 1989, Bodie et al. 1995). Little emphasis has been placed on the training process observers must undergo before they become competent (Dirschl et al. 1981). What we see is what is known, but what is missed is unknown. Weather, lighting conditions, season, heterogeneity of terrain, vegetative cover, observer fatigue, search speed, altitude, and distribution of the subject species all affect what is seen (Simmons and Hansen 1980, Remington and Welsh 1989, Bodie et al. 1995).

Airborne IR has been used to survey a range of species and habitats (Table 1). Two advancements in IR sensors have made them useful for wildlife surveys: the decrease in minimum detectable thermal resolution to less than 1 C, and the increase in the number of pixels. These 2 characteristics allow detecting the animal against a wide range of environmental conditions and allow easy identification by body shape. For example, a portion of a deer may be detected under a tree and, by orbiting to provide a better visibility angle, the deer's ear can be identified. IR provides higher detection rates for a given swath width than an aerial survey with human observers with few exceptions.

An IR system mounted on an airplane will cost less than human observers in a helicopter. Further, IR allows for higher flight altitude above ground level. Flight altitudes (e.g., 160 m) used by human observers provide little room to recover from mechanical failures or pilot error.

Using airborne IR for wildlife surveys requires: 1) knowledge of animal behavior and wildlife surveys, 2) an understanding of thermography and sensor capabilities, and 3) selecting the correct airplane or helicopter. Infrared can be used during day and night and year round depending on the survey objective and animal behavior. Knowledge of sampling as well as habitat use and behavior of the subject animal is required for an airborne survey.

Sensor Technology

An infrared sensor captures the emitted IR energy and converts it to a visual image. Infrared energy is transmitted through 2 atmospheric windows, the short (2–5.5 μ) and long wave (8–14 μ) with the middle band (6–7 μ) largely absorbed by the atmosphere. Detectors are designed to transform incident infrared radiation to an analogue signal. This signal is displayed on a screen and the level of infrared energy emitted by objects can be viewed. Typically, sensor detectors are designed to detect either short or long waves. Short wave sensors are better than long wave sensors in warmer more humid environments but fail in extremely cold environments. Long wave sensors have more solar immunity and are less likely to add solar reflectance from water surface or other reflective surfaces such as some rock types. IR sensors cannot detect infrared energy through windowpanes unless the sensors are designed to detect energy below 2 μ.

Sensor Type

There are 2 general types of sensors: radiometer and imaging infrared (also referred to as an IR viewer). Radiometers provide the ability to measure the temperature by calibrating across the image and by measuring variables such as distance, emissivity, and ambient temperature. Some radiometers allow use of isotherms and have an array of palettes to enhance features of interest. Infrared viewers provide a general reference of which objects in the scenes are warmer and colder but there is no way to measure actual temperature. Infrared viewers provide relative temperature using several reference points (low and high temperatures) of known temperature in the scene. However, this approach incorrectly assumes the sensor responds linearly to increases or decreases in temperature. For example, if white is set to represent the hottest points in the scene, a white object on the north side of a canyon may be cooler than a white object on the south side.

Scanning vs. Focal Plane Array

In the past, scanning technology was used to collect emitted energy. One detector moved across the entire image using a rotating mirror to measure emitted energy. It had to collect data at a quarter of a million points within a thirtieth of a second to form an image. Increasing the number of detectors scanning across an image allows more time at each point. The one detector system had substantial distortion and detecting animals was difficult; these systems often required further computer enhancement. Newer systems provide an image with sufficient detail to appear to be a black and white photograph rather than an IR image. Scanning systems allow for capturing a low reference temperature point prior to scanning the images and a high reference temperature point after capturing the image. This provides an opportunity for thermal calibration.

Focal plane array is similar to film in a camera, but the film is replaced with sensor cells. In an infrared system, there is an array of individual detectors (i.e., 340 × 220). A focal plane array doesn't capture a reference point but has a "flag" or a plate with a well-known temperature that covers the array for a second. This calibration can be set for some interval, typically 10–20 minutes, or the operator can push a button to initiate the flag.

Currently, focal plane array systems allow for a smaller minimum detectable thermal resolution than scanning systems (0.07 vs. 0.1 C). A minimum detectable thermal resolution of 0.1 C, however, is sufficient for wildlife applications. To date, scanning systems can provide a larger number of pixels than currently available in a focal plane array. The advantage of more pixels in an infrared system is that they allow more detail.

Hand-held Fixed Position and Gimbal Systems

A hand-held infrared system used from the door or window of an airplane or helicopter can result in significant blur resulting in distorted temperature readings. More troubling are issues of operation safety, fatigue, and wear and tear on equipment. Hand-held systems are relatively inexpensive but require slow airspeeds for good image quality. Looking through a viewfinder while in the air is a poor option for large areas. Fixed position and gimbal systems are mounted (with FAA approval) on an airplane or

Table 1. Wildlife species that have been surveyed using an infrared sensor.

Species	Habitats	Reference
Sandhill cranes (*Grus canadensis*)	Population counts, Platte River, Nebraska	Sidel et al. 1993
Malleefowl (*Leipoa ocellata*)	Incubator-nest mounds, Northwestern Victoria, Australia	Benshemesh and Emison 1996
Canada geese (*Branta canadensis*)	South Dakota	Best et al. 1982.
Birds: Canada geese, Great horned owl (*Bubo virginianus*), Pileated Woodpecker (*Dryocopus pileatus*), Northern Flicker (*Colaptes auratus*), Barrow goldeneye (*Bucephala islandica*), Bufflehead (*B. albeola*), Mallard (*Anas platyrhynchos*), Green-winged teal (*A. crecca*), Lapland longspur (*Calcarius lapponicus*), Pectoral sandpiper (*Calidris melanotos*)	Nests and individuals, Arctic tundra	Boonstra et al. 1995
Whales: minke (*Balaenoptera acutorostrata*), humpback (*Megaptera novaeangliae*), fin (*B. physalus*), blue (*B. musculus*), sperm (*Physeter macrocephalus*)	Northern coast, Norway	Cuyler et al. 1992
Walrus (*Odobenus rosmarus*)	Northwest Territories, Canada	Barber et al. 1991
Moose	Deciduous and mixed coniferous forests, New Hampshire	Adams 1995
Red squirrels, Arctic ground squirrel (*Spermophilus parryii*), snowshow hare (*Lepus americanus*), meadow jumping mice (*Zapus hudsonius*)	Individuals, nests, and burrows; Arctic tundra	Boonstra et al. 1994
Gray Bat (*Myotis grisescens*)	Caves, northern Alabama	Sabol and Hudson 1995
White-tailed deer (*Odocoileus virginianus*)	Deciduous forests, United States	Wiggers and Beckerman 1993, Garner et al. 1995, Naugle et al. 1996, Havens and Sharp 1998
Roe deer (*Capreolus capreolus*), muntjac (*Muntiacus reevesi*), red deer, fallow deer (*Dama dama*), sika deer (*Cervus nippon*)	Deciduous and coniferous woodlands, United Kingdom	Gill et al. 1997
Moose, wild turkeys (*Meleagris gallopavo*)	Deciduous forests, Eastern United States	Garner et al. 1995
Elk	Coniferous forests, southwestern United States	Dunn et al. 2002

helicopter. These systems allow GPS data to be recorded directly on the video. Fixed position sensors are mounted so their orientation is pointing straight down or nadir. These systems are good for mapping purposes but differentiating between species can be difficult because only one angle is provided. Housing a sensor in a gimbal that has 4 stabilized axis helps decrease image blur. The operator controls the system using a "joy stick" and monitor from inside the airplane providing a wide range of visibility angles. Natural color video cameras can also be housed in the gimbal to provide video referencing.

These fixed or FLIR systems have 1 to 3 fields of view (FOV), which are similar to camera lenses. The FOV and altitude above ground level (AGL) are used to calculate the area on the ground viewed by the sensor. The slant range or the hypotenuse of the triangle should be used if the sensor is oriented other than straight down. If the sensor is pointing to an oblique angle, the calculated width (convert degrees to "mils" where 1 degree = 18 mils) is for the image center. A 3-degree field of view spans 3 × 18 or 54 mils. For example (English units are used in aviation):

where
AGL = 2,500 ft., the down look angle = 35 degrees,
SIN of 35 degrees = 0.5735, and with a 10 degree FOV = 180 mils.

Thus:
slant range = 4,357.5 (2,500 AGL / 0.5735), and
width of view = 784 ft. (180 mil FOV × 4,358 ft. slant range).

Airborne Platforms

Infrared systems have been mounted (requiring a specially-designed mount) on helicopters and airplanes. Helicopters have the advantage of being able to operate at slow speeds and at low altitudes but along with higher costs, can have greater vibration, which can degrade the image. Fixed-wing aircraft provide less vibration and cost less. Power for the sensor, GPS and video equipment is an issue, as most systems require 24–28 volts.

Most light airplanes and helicopters follow visual flight rules (VFR). Both day and night operations are possible using VFR depending on the lights available in the survey area. However, night flights in mountainous terrain or in areas with little light sources require instrument flight rules (IFR) that could require a twin-engine airplane for safety.

Accuracy Assessment of Remotely Sensed Data

A variety of devices and techniques, such as Landsat Imagery and FLIR, can be used to record characteristics of the earth's surface from remote positions. However, interpretation of remotely sensed data can introduce error (Janssen and van der Wel 1994). Error in mapping can be generated in several ways, error in thematic classification, both by omission and by misclassification (commission) (Story and Congalton 1986), as well as error in cartographic delineation (location error).

Accuracy assessment of landscape maps generated from remotely sensed data is generally accomplished through field verification of a select subset (samples) of thematic or areal map units. The investigator must identify accuracy assessment objectives as well as the level of error acceptable for accuracy estimates (based on planned uses of the map). To keep the sampling design simple, easy to analyze, and statistically robust, it is important to define the sampling unit and to use a basic probability sampling design (inclusion probabilities are equal and nonzero for all members of the population). Design–based statistical inference can be applied when sampling is of characteristics of a real, explicitly defined population (Stehman 2000). Probability sampling designs can be interpreted as accuracy estimates for the entire population via established statistical estimators that vary according to the particular sampling design (Stehman 1999). Limitations of resources for field verification or site access can constrain a sampling design. Sampling designs that meet the requirements of equal probability sampling are: simple random sampling, systematic sampling, stratified systematic unaligned sampling, and one-stage cluster sampling (Stehman and Czaplewski 1998, Stehman 1999).

Investigators initially developed the confusion or error matrix, which permitted calculation of simple test sample ratios (the number of land use classes incorrectly depicted on the map divided by the number of correctly depicted land use classes confirmed by field verification) (van Genderen et al. 1978, Fitzpatrick-Lins 1981). Since those efforts, a great variety of error matrix interpretations and new error metrics have been presented in the literature. The most important contributions of recent work for accuracy findings have been the increase in statistical rigor and decrease in confidence intervals (Richards 1996, Stehman 2001).

Identification of the classification error in maps is accomplished using an *a priori* target level for thematic map accuracy and designing the assessment procedure (number of sampling points, etc.) based on statistical parameters (Fitzpatrick-Lins 1981). There are a variety of methods for setting the number of sample points from the stratified systematic unaligned sampling technique (Rosenfield et al. 1982) to statistically derived sampling levels based on the assumption that samples have normal distributions (Hord and Brooner 1976). Other options include decision-rules processes that can incorporate cover type stratification, cover type abundance weighting, and differential sampling effort.

An estimation of sampling intensity can be based on tables with sample data represented as $x = 1$ for a correct interpretation, and $x = 0$ where the map interpretation is incorrect. Consequently, x has the probability density function for a single observation (Rosenfield et al. 1982):

$$f(x) = p^x (1 - p)^{1-x}, 0 \leq p \leq 1, x = 0,1.$$

With prior probability estimates, sampling levels could be established based on the cumulative binomial probability that is bracketed with confidence intervals:

$$P_B = {}^{n-k(n)-1}\Sigma_{s=0}\, C_s^n\, p_o^{n-s} (1 - p_o)^s,$$

where n = sample size, $k(n)$ = largest integer less than or equal to $n(p_o + E)$, E = the error of the estimate (the maximum error we can tolerate), and p_o = the *a priori* value based on experiential knowledge.

Variation in size and frequency of thematic cover types necessitates adjustments in sampling intensity that reflect their relative importance. Thus, a cover type with limited occurrence can be sampled with greater frequency, while those most common and abundant will be sampled according to statistical parameters. Stehman (2001) reported that sample size required to achieve a standard error of 0.05 for a population estimate reaches a maximum of 100, when population size is $\geq$10,000 [for populations of <10,000, the sample size required to achieve SE = 0.05 is a function of $n = N/(0.01N + 1)$ where n = sample size and N = population size].

The error matrix is composed of orthogonal axis with cover types (Fig. 14) and allows analysis of accuracy and error rate for each cover type. Cover type accuracy is measured by dividing the number of correctly classified sample points for each cover type by total points sampled. Map accuracy can also be presented as user's (diagonal values divided by row totals for each matrix) and producer's (diagonal values divided by column totals for each matrix) values for each cover type, which are the converse of commission and omission error, respectively.

Map accuracy assessment can be handicapped by limitations in field verification procedures (i.e., limited access to sample points can introduce error into the assessment), and there is a chance that interpretation of cover type will not be equivalent between the map producer and those performing the map accuracy assessment. Linguistic variables can be used to quantify field verification confidence values that can then be used to calculate a new set of values for map accuracy (Gopal and Woodcock 1994, Woodcock et al. 1996). Confidence values are factored into the proportion that each contributed to the total individual cover type sample (Woodcock et al. 1996). An example could be labeled Derived Accuracy Assessment Values (DAAV), a new metric that uses confidence values for each sample point factored into the overall accuracy value calculated for each cover type. For example, let the field confidence ratings range from 0 to 5:

where

0 = no access to sample point (value = 0.0);
1 = low confidence, limited access to sample point or map class, a poor match to field-verified class (value = 0.2);
2 = low confidence, access incomplete or map class a poor match to field-verified class (value = 0.40);
3 = location of sample point not easily ascertained, field verification of class based on proximate class or problems with class match to map class (value = 0.6);
4 = confidence high in field-verification of sample point location and class match (value = 0.8); and
5 = sample point is acquired and matches map class designation (value = 1.0).

If a specific cover type had 109 sample points visited of which 92 were correctly classified and 89 had a confidence value of 5; the proportion of confidence value 5 of the correct points is 89/92 = 0.97. The confidence value for a rating of 5 is 1.0 (the multiplier = 1.0) or 0.97 (1.0) = 0.97 and the class accuracy is the percentage of correctly classified sample points in the cover type (92/109 × 100 = 84%). Thus, 0.97 (84%) = 81.5% is the DAAV for confidence value 5. The DAAV for the confidence value of 5 is then combined into an overall value based on the sum of all confidence values for samples of the class; the DAAV for each confidence level recorded for the class sample = overall class accuracy.

The assessment of map accuracy by field verification could benefit from methods that increase the accuracy of sample point capture (Woodcock 1996). This could be accomplished by tagging the sample points with location information (UTMs, Latitude and Longitude), which could be targets for field verification. GPS units could help in quantifying variability encountered in accessing sample points. Further, proximity to each sample point could be quantified and used in the assessment of map accuracy.

The overall objective of performing an accuracy assessment of a map is to provide a quantified measure of how well the map represents reality. If proper procedures are followed in the design, performance, and analysis of sampling, the accuracy assessment results can be used as an integral part of the map.

SUMMARY

All projects, whether habitat or animal related, occur spatially in wildlife biology and management. Thus, spatial technologies can be used to evaluate research and management efforts. This chapter provides a brief look into using 3 spatial technologies: GIS, GPS, and remotely sensed data (Landsat Imagery and FLIR) along with highlighting the need to understand data documentation, data accuracy, and Internet applications. Spatial technologies should be considered as tools to assist resource managers with mapping, and as a way to merge or incorporate data sets from a variety of sources into one format. Maps can focus discussion by presenting what is known or thought to be known about an area or issue. Additionally, most people readily accept maps because they are easier to understand at first glance than some tables or figures, and because many people use them to navigate across town or across a country. Spatial technologies rely on computer technologies and currently are expensive to develop and maintain. However, their value outweighs their costs when information is incorporated into products, which help managers make wise decisions about natural resources.

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