APPLICATION OF SPATIAL TECHNOLOGIES IN WILDLIFE BIOLOGY

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INTRODUCTION

The Information Age is here, and technology plays a large and important role in gathering, compiling, and synthesizing data. The old adage of analyzing wildlife data over "time and space" today implies use of technologies including their integration into research and monitoring studies as well as evaluation strategies. Thus, resource managers must understand how to use these technologies, especially in regards to evaluating and assessing land at various scales, i.e., site, watershed, sub-basin, and basin levels. To assist resource managers with this task, this chapter explores spatial technologies that are commonly used by wildlife managers to acquire, compile, and interpret data. These include: Geographic Information Systems (GIS), Global Positioning Systems (GPS), and using remotely sensed data, which are Landsat Imagery and Forward Looking Infrared (FLIR).   This chapter will also highlight an awareness 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 when there is a concern, managers find themselves with a lack of information. Spatial technologies provide tools to incorporate and analysis 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 a map. These technologies provide a means to handle complexities, such as incorporating scale and hierarchy concepts into ecosystem-based management approaches (O'Neill 1996). Additionally, these technologies allow spatial depictions of theorical concepts, like total diversity 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.

Using spatial technologies should be thought of 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 decision-makers. Spatial technologies, like GIS, are frequently described in terms of hardware (computers and workstations) 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 and to effectively transcribe data in and out of their system requires peripherals like tape storage and retrieval systems, CD-Rom and DVD-Ram writers.

The first spatial technology addressed is GIS, which is a general-purpose technology for handling geographic data in a digital form. GIS has the ability to: preprocess large amounts of data into a form suitable for analysis and evaluation; support models that perform analysis, calibration, forecasting, and prediction; and post-processing of results to produce tables, reports, and maps (Goodchild 1993). For a more technical description on what GIS is and how it works, please review the 5th Edition techniques manual, Chapter 21-Geographic Information Systems (Koeln et. al. 1996).

USING GLOBAL POSITIONING SYSTEMS

This section provides the user with an understanding of the Global Positioning System (GPS) and how to use it. There are several self-help guides (Letham 1998; Anderson 2002) if one desires a more in-depth understanding of GPS. GPS 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 boils down to the velocity that a satellite signal travels versus the time it takes the satellite 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” pluses. The signal looks like random electric noise, however, in actuality the noise is a series of complex patterns that help ensure the 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 another satellite's signal. 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.

Box *#4* Here!

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-demensional 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 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 you want to have precise positioning will require 4 channels so that it can make 4 measurements simultaneously. But for triangulation to work, you also need 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 that 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 measurements; it is complex and can only be found as a feature on advance 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.*

The military maintains the most precise system that is 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 scrambling of the GPS broadcast so that a greater accuracy (1 - 10 m) could be obtained for commercial or nonmilitary uses.

Box #5 Here!

Differential Correction for GPS

Differential GPS involves 2 receivers that are in relatively close proximity (typically within ~ 200 kilometers); 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 provided to 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. You would then have to buy data from a reference receiver and establish a communication link to your 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 GPS utility to fix an airplane’s location in real-time, the Federal Aviation Agency (FAA) has developed, Wide Area Augmentation System (WAAS) that would extend coverage for differential GPS for 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 improving capacity and safety. Ultimately, WAAS allows GPS to be used as a primary means of navigation from takeoff through Category I precision approach (i.e., close to the runway but not zero visibility; Category 3 landings are zero visibility). The ramifications of the FAA to maintain this system go well beyond aviation; because of its design the system helps ensure that differential GPS corrections will be accessible to all whom need them. To learn more about WAAS, please see the Garmin website at: www.garmin.com/aboutGPS/waas.html.

Box #6 Here!

Using GPS

In using GPS, there are 2 main questions to be answered 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? Further to help set up the GPS unit, you need to be familiar with some data capturing and processing terms.

Data Dictionary/Metadata

Discussion of the data dictionary……

Other information that should be addressed when collecting and processing GPS data is metadata documentation. Data collected through use of GPS equipment and techniques should be documented in the metadata following the Federal Geographic Data Committee standards (FDGC 1998). Documentation in the metadata should cover the various aspects of GPS data collection and processing including but not be limited to those below:

- **Horizontal Position Accuracy –** accuracy achieved after differential GPS methods have been completed.
- **Horizontal Position Accuracy Report –** explanation of how the horizontal position accuracy was achieved. To include type and accuracy of GPS equipment used, settings used in data capture and receiver calibration including number of epochs recorded at each position, logging interval of each source, number of satellites available, elevation mask used, PDOP value, and accuracy achieved from differential correction and High

Accuracy Reference Network points. Post processing techniques should also be addressed here.

- **Lineage –** under the appropriate subheading information on date and time of data collection and people involved in data collection and, if applicable, their credentials.
- **Process Step –** a detailed description of methodology on how the data were collected and processed. This will include detailed information on both field GPS and base receivers used in differential correction, data collection methods, details on post processing software and method, and the coordinate and unit system used for data collection.

GPS Uses in Wildlife

What are the practical applications for 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 and 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*) (Servheen and Waller 1999), caribou (*Rangifer tarandus*) (Dyer 1999), mountain lions (*Puma concolor*) (Bleich et al. 2000) and wolves (*Canis lupus*) (Merrill and Mech. 2000).

These collars now come in different sizes and can be used on small, midsize or large mammals. The weight varies from 100 to 2,100 g (depending on collar size), and they can store up to 10,000 locations [non-differentially corrected or 5,000 locations differentially corrected] depending on recording frequency and battery configuration. They operate in temperatures ranging from –30 ^{o} to +50 ^{o}C, and the data can be retained in the collar at temperatures ranging from –50 ^{o} to +75 ^{o}C. Collars can be configured to allow periodic data downloads, or all the data can be transferred to a computer when the collar is retrieved. A source of concern, however, in using GPS collars lies with locating an animal, like elk (*Cervus elaphus*) 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 ($P \leq .01$) between failure of GPS location attempts and tree density, tree basal area, and 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, could also influence receiving GPS signals. However, Johnson (pers. comm. 4/16/2003 – ODFW Research Biologist, LaGrande Oregon) stated that because of recent technology advancements their recent evaluation of GPS collars showed much better than 60% in stands >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 (Martischang 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 would allow one to store information right on the map. This requires the ability to create a moving map, which occurs when GPS receiver takes the information and displays its current position on the map and as you move, the map also moves. This way they can be assured of their locations and the location of what they are classifying. Currently, GPS can be directly linked to laptop computers. GPS communicate to the computer by typically 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, SOLO CE by Tripod Data Systems, and ArcPad by ESRI. In each program, the primary function is to collect positions, attribute these data, as well as locate existing points in the field.

The future for GPS will see units becoming smaller, and the technology becoming more wide spread for non-commercial uses. We can also expect to see GPS to work more effectively with satellites like ARGOS whereby GPS data is uplinked to a satellite periodically and then downloaded at 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 very small animals. GPS World Magazine (www.gpsworld.com), *Telonics Quarterly* (www.telonics.com) or *GeoCommunity* (www.geocomm.com) bring together a great deal of information about the current state of GPS and GeoSpatial technology issues and their applications. For a link to a GPS Glossary of Terms, please see Navtech's site www.navtechgps.com/glossary.asp. Finally, with more and more people using GPS, the resource managers will face new problems. One such 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.

LANDSAT Imagery

Remote sensing has been used in wildlife biology for many years. Historically, small format aerial photographs have been the most commonly used method of remote sensing used for mapping habitats. With the improvements in software and hardware, plus the reduction in costs for software, hardware, and Landsat imagery, remote sensing is becoming a frequently used tool for mapping habitats, particularly over large regions (state and regions). Ducks Unlimited (a non-profit wetlands conservation organization), working with NASA in the early 1980's was an early pioneer in the use of Landsat imagery to map waterfowl habitat (Koeln et al. 1988). Today, many non-profit conservation organizations, state wildlife agencies, and US Federal resource management organizations, such as the US Fish and Wildlife Service, the US Forest Service, the Bureau of Land Management, rely upon Landsat imagery for mapping and monitoring habitat. Since the early 1980s, Landsat imagery has been used in the management of waterfowl, grouse, quail, sandhill cranes, squirrels, turkeys, deer, elk, bear, and many other species. Palmeirim (1985) used Landsat imagery to identify ruff grouse (Bonansa umbellus) habitat for potential release sites for reintroduction in Kansas. Hepinstall and Sader (1997) used Landsat imagery and breeding bird surveys data to model the probability of various bird species occurring within areas of Maine. National Biodiversity GAP Analysis Project uses an approach to locate areas of high biodiversity in order to preserve these areas. GAP Analysis is being conducted by many states and requires three layers: vegetation, vertebrate, and land stewardship (Scott et al. 1993). Most states are using Landsat imagery for mapping the vegetation (Lillesand et al. 1998; ; Kiilsgaard and Barrett 1999 and 2000).

History of Landsat

On July 23, 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). When operational orbit was achieved, it was designated ERTS-1. The satellite continued to function beyond its designed life expectancy of 1 year and finally ceased to operate on January 6, 1978, more than 5 years after its launch date. The second in this series of earth resources satellites (designated ERTS-B) was launched January 22, 1975. It was renamed Landsat 2 by NASA, which also renamed ERTS-1 to Landsat 1. Four additional Landsat satellites were launched in 1978, 1982, 1984 and 1999 (Landsats 3, 4, 5, and 7 respectively). Landsat 6 was launched on October 5, 1993, but failed to achieve orbit. Each successive satellite system had improved sensor and communications capabilities.

Landsat 1, 2, and 3 carried two 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. Landsat 1 and 2 carried three RBV cameras that imaged a 185 km by 185 km area in the green, red, and near infrared. Landsat 3 used two panchromatic RBV cameras, each imaging half of the 185 km swath. RBV cameras in

Landsat 1, 2, and 3 were designed to be the primary imaging systems on Landsat. However, technical problems on all three 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.

Like the RBV cameras, the MSS was used to image a 185 km swath. Each pixel (picture element) imaged an area somewhat less than a football field (79 m by 57 m). Landsat 1 and 2 MSS sensors imaged in green, red, and two different wavelengths of the near infrared, while the MSS sensor on Landsat 3 imaged the same four bands as Landsat 1 and 2 and imaged a 5^{th} band in the far infrared (10.4-12.6 microns).

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. The TM sensor provided significant improvement to remote sensing. The TM sensor records 7 bands of information for each pixel in the following spectral regions: blue-green, green, red, near infrared, two wavelengths of mid-infrared, and far infrared. The routine collection of MSS data by Landsat 5 was terminated in late 1992.

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

Characterization of Landsat

The Landsat satellites orbit in a polar (north to south path), sun-synchronous orbit at a nominal altitude of 920 km above the earth for Landsats 1-3 and 705 km above the earth for Landsats 4, 5, and 7. A sun-synchronous orbit ensures that the satellite always 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 the seasons, every Landsat scene has the illumination of the same time of day. The Landsat 4, 5 and 7 orbit has an equatorial crossing time of 9:45 a.m. 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. Figure 1 shows a full Landsat scene for a scene acquired near Frederick, MD. Scene locations are identified by path and row. For Landsats 4, 5, and 7 233 paths are required to cover the entire earth. Each path is divided into 119 rows.

Table 2 summarizes the spectral bands imaged by the Landsat systems. 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 is designed for detecting chlorophyll absorption in vegetation. MSS bands 3 and 4 are 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 two mid-infrared bands on TM are useful for vegetation and soil moisture studies, and 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. Figure 2 shows all nine bands of the ETM+ sensor for a portion of a Landsat scene.

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

Digital Image Processing

To be effective in management decisions, maps and geographic information systems (GIS) requires timely and accurate information. Remote sensing and digital image processing have the potential to meet these needs. Digital image processing is the process of enhancing digital images, often to aid in the manual interpretation of information from digital images and the process of automated extraction of information from digital images. In the near future, there will be an unprecedented availability of digital data from satellite sensors in response to the concerns about human impacts on the earth, habitat monitoring, and global climate change (Ormsby and Soffen 1989). 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 models 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).

Understanding of remote sensing models and their interrelationships can benefit from a system view of the image-forming process (Swain and Davis 1978). An important concept is the distinction between the scene, which is real and exists on the earth's surface, and the image, a collection of spatially arranged measurements from the scene (Strahler et al. 1986). The purpose of a remote sensing model is to provide a conceptual and explicit framework for inferring the characteristics of the scene from the image. A remote sensing model may be generalized as having three components: a scene model, an atmospheric model, and a sensor model.

A scene model quantifies the relationships of the objects or targets of interest and their interactions with radiation through the processes of reflectance, transmittance, absorbance, and emittance. Characteristics of the scene objects could include their type, size, number, and spatial and temporal distributions. The model also must consider the background or nontarget components of the scene, including shadow.

An atmospheric model describes the transformation of the radiance due to scattering by molecules and aerosols, and gaseous absorption during the path from the sun to the earth's surface and between the surface and the spacecraft. If an atmospheric model is omitted, the parameters developed to extract information from the image are not transferable and the entire procedure must be repeated for other images. Several methods for the normalization or radiometric calibration of remotely sensed data have been developed (Ahern et al. 1987, Schott et al 1988, Chavez 1989, Tanre et al. 1990).

The sensor model quantifies how the instrument collects the measurements of the scene and includes four key parameters: spectral, spatial, and temporal resolution, and view angle (Duggin 1985). The spectral resolution of the sensor specifies what wavelengths of the electromagnetic spectrum are measured. The spatial resolution specifies the size of the area on the ground from which the measurements that comprise the image are derived. The spatial resolution relative to the spatial structure of the scene objects determines the appropriate analysis methods for scene inference (Woodcock and Strahler 1987). The temporal resolution specifies the frequency with which images are obtained in time. View angle is an important component of the imaging geometry. View angle and illumination geometry (solar zenith and azimuth angles) are important determinants of the measured reflectance since adjustments in observation and illumination geometry result in different sampling of the bidirectional reflectance distribution function, the most fundamental property describing the reflection characteristics of a surface (Silva 1978).

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

Image enhancement involves the 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 data in a study of wood stork foraging habitat. Jackson (1983) provided a general procedure to develop spectral indices for user-defined features in a scene.

The development of scene models 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 scene models given the 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. A discrete scene model is appropriate when the scene objects are larger than the spatial resolution of the sensor.

The parameter estimation process for spectral classifiers can be generalized as being supervised or unsupervised (Swain and Davis 1978, Schowengerdt 1983). In supervised classification, a sample of image elements for each landcover class is used to estimate parameters, typically a mean vector and covariance matrix, for input to the classifier. In unsupervised training, a clustering algorithm is used to partition a sample of the data into populations of pixels with similar reflectance, which are referred to as spectral classes and parameters estimated for these spectral classes (Richards and Kelly 1984). In unsupervised training, the analyst then attempts to establish a correspondence among the spectral classes and the landcover classes. A statistics file consisting of a mean vector and covariance matrix for each landcover class then is input to a classification algorithm. The output 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 landcover class for which the a posteriori probability was the maximum. Figure 3 shows an example of land cover derived from a Landsat 7 ETM+ scene using an unsupervised classification approach. An enhancement to the standard output from the maximum likelihood classification would be to create a raster for each landcover class wherein the pixel value would be the a posteriori probabilities of membership for the category. The result is a probabilistic digital map of the geographic distribution for each landcover class. This would increase the computational and storage requirements, but technological progress in these areas is great (Faust et al. 1991).

In a continuous-scene model, 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 coverage, is established and used to estimate the property in each pixel in a continuous fashion. Figure 4 shows an example of percent canopy coverage derived from a Landsat ETM+ image. Mixture models are a type of continuous-scene model, in which 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 the properties and processes at the land surface. A variety of spectral-spatial models are available. Some of these scene models segment the image into contiguous groups of pixels that meet a spectral similarity criterion and perform the classification using all the pixels of the feature (Strahler et al. 1986). Figure 5 shows the results of image segmentation. 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 the 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 (NDVI), calculated from the red and infrared spectral reflectance measurements of the AVHRR sensor, have been used to describe and map the intra- and inter-year phenological dynamics of biomes at regional, continental, and global scales (Justice et al. 1985), to infer net primary productivity (Goward et al. 1985), and to measure the dynamics of vegetation at the transition zones between biomes (Tucker et al. 1991). Various techniques for detecting change (Singh 1989) use images acquired at different times to infer changes in land cover. Figure 6 shows areas of wetland changes as derived from Landsat imagery using a technique called Cross Correlation Analysis (Koeln and Bissonette 2000).

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

Obtaining Landsat Imagery

The Landsat Program is a joint initiative of the U.S. Geological Survey (USGS) and the National Aeronautics and Space Administration (NASA) to gather earth resource data using a series of satellites. NASA has been responsible for developing and launching the spacecrafts, 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 at the USGS's EROS data Center (EDC) in Sioux Falls, South Dakota. Daily, over 250 Landsat 7 scenes are downloaded to the EDC receiving station. 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 over EDC. 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, the spatial coverage required (by geographic coordinates, place name, or path/row), acquisition date, and other requirements. See Figure 7 for example of the search tool. The results of the search are immediately provided and the user can preview any of the scenes returned from the search and order the scenes that best meet the requirements. An example of the results of and EarthExplorer search is shown in Figure 8. Each Landsat scene ordered costs $600 ($480 per scene when ordering 25 or more scenes) and can be placed on an FTP site for downloading by the purchaser or can be shipped to the purchaser on CD-ROM.

Other sources of Landsat Imagery

The scenes that you obtain from EDC will not be precisely registered 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^{TM}-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, MD 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.

The GeoCover^{TM}-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 meter (RMS) geodetic positional accuracy. The Landsat source images have been hand picked from the Landsat archives of the EROS Data Center and the international ground stations, and represent the highest image quality and lowest cloud cover available for the specified time period. GeoCover^{TM}-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 which not only can be used as a geodetically accurate base map, but also provide 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.

Working initially with NASA and currently with NIMA, EarthSat has developed a set of procedures and processes to produce a landcover analysis for all land areas of the world using Landsat TM and ETM+ data rectified under the GeoCover^{TM}-Ortho program. These images can be obtained from EDC for $65 per scene. Landsat imagery provides an excellent tool for mapping the landscape and analyzing changes that have occurred in the landscape. It provides an economical tool (less than $.02 per square kilometer) that has historically been underutilized by natural resources managers. With the reduction in the cost of imagery and improvements and reduction in costs of computers and image processing software, Landsat imagery will be utilized more frequently in the future.

Forward Looking Infrared (Flir) For Wildlife Surveys

Conducting an Accuracy Assessment of Remote-sensed Data

A variety of devices and techniques can be used to record characteristics of the Earth's surface from remote positions. The interpretation of remote-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. When attempting accuracy assessment of a mapping project, improper sampling and interpretation of statistical findings can introduce further error. Early on, investigators developed the confusion or error matrix, which permitted the calculation of simple test sample ratios: The number of land use classes incorrectly depicted 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 have been the increase in statistical rigor and the decrease in confidence intervals of accuracy findings (Richards 1996).

Determination of the classification error in maps is accomplished by 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 various methods for setting the number of sample points, from the stratified systematic unaligned sampling technique (Rosenfield et al. 1982) to statistically derived sampling levels that are based on the assumption that the samples have normal distributions (Hord and Brooner 1976). Other options include decision-rules processes which can incorporate cover type stratification, cover type abundance weighting, and differential sampling effort.

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

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

(Rosenfield et al. 1982). With prior probability estimates we can establish sampling levels based on the cumulative binomial probability that is bracketed with confidence intervals:

$$P_B = {}^{n - k(n) - 1}\Sigma_{s = 0}\, C_s^n\, p_o^{n - s}(1 - p_o)^s \qquad (2)$$

where n = sample size, k(n) = largest integer less than or equal to n(po + *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 the size and frequency of thematic cover types necessitates adjustments in sampling intensity that reflect the relative importance of the cover type. Thus, a cover type with limited occurrence can be sampled in its entirety, while the more common and abundant cover types will be sampled according to statistical parameters.

The error matrix is composed of orthogonal axis with cover types (Table 3). The error matrix allows analysis of each cover type accuracy and error type. Cover type accuracy is determined by dividing the number of correctly classified sample points for each cover type by the total points sampled for each cover type. Map accuracy can also be presented as user's (matrix diagonal values divided by matrix row totals) and producer's (matrix diagonal values divided by matrix column totals) 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.

Field verification confidence can be quantified and confidence values can be used to calculate a new set of values of map accuracy. Confidence values are factored into the proportion that each confidence value contributed to the total individual cover type sample. A new metric (Derived Accuracy Assessment Values (DAAV)) would combine the weighted average overall accuracy value calculated for each cover type. For example, let the confidence ratings range from 0 – 5:

0 = no access to sample point (value= 0.0)

1 = very low confidence; very limited access to sample point or map class a very 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 determined, 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)

5 = sample point is acquired and matches map class designation (value= 1.0)

If cover type (1) had 109 sample points, of which 89 had a confidence value of 5. The proportion of confidence value 5 of the total is 89/109 = 0.82. The value for confidence 5 is 1.0 so the class accuracy is the percentage of correct sample points in the cover type

(89/109x100 = 82%). For a confidence value of 5 for cover type 1 the DAAV is 0.82(82%) = 67.24 %. The DAAV for the confidence value of 5 is then combined into an overall value based on the weighted average of all confidence values (overall cover type accuracy = confidence value accuracy percentage x proportion of cover type data for confidence value).

The assessment of map accuracy by field verification could benefit from methods, which increase the accuracy of sample point capture (Woodcock 1996). This could be accomplished by tagging the sample points with location information (UTM,s or Latitude and Longitude) which could be targets for the field verification. Global Positioning System units could help in assessing variability encountered in accessing sample points. Proximity to sample point could be quantified (GPS error incorporated) and used in the determination of map accuracy.

Conservation GIS and the Internet

Any conservation project implementing GIS will undoubtedly want to take advantage of Internet technologies. With the widespread development of data clearinghouses, the Internet has become the key medium for GIS data and metadata awareness and exchange. Specialized GIS users groups and organizations such as the Society for Conservation Geographic Information Systems (http://www.scgis.org) are invaluable tools as well. In addition to using these resources to develop their GIS, most conservation organizations will want to develop their own Internet sites to deliver their GIS information to their target users. This section outlines how conservation GIS users may incorporate Internet technologies into their GIS programs and projects. It finishes 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. Many data sets for developing countries, such as the Digital Chart of the World, as well as specific national level coverages, have been prepared by agencies and organizations outside the country. Internet search engines, such as ***Google*** (http://www.google.com) or ***Yahoo*** (http://www.yahoo.com), can be easily used to search for desired data by keywords. This method sometimes yields good results, but better success is often achieved by searching a data clearinghouse or portal specifically focused on GIS data and/or your desired region. There are many such sites. 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 more specific focus on biologic data and analysis tools. These are just two examples of the ever-increasing number and variety of Internet resources for finding existing GIS data.

Another major focus of the Internet is to acquire and deliver GIS data. Most GIS projects today develop a web site to promote their project and to deliver results and data. The data search tools mentioned earlier often direct users to these sites where the actual GIS data can be obtained, either by direct download or ordering the data. Some sites, such as the GIS Data Depot (http://www.gisdatadepot.com/), have made a business of collecting and delivering, typically for a fee, GIS data from a wide variety of sources while sites that actually produce and maintain their own data often allow free GIS data downloads (http://www.nwhi.org). Government and non-profit groups typically operate these free data sites. In addition to delivering raw GIS data, many of these sites are developing 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 via the Internet. The remainder of this section will elaborate on these GIS-Internet applications.

GIS and Internet programming technologies are rapidly changing. Currently, GIS web applications can be divided into two basic types, static and dynamic. Static applications are those that serve pre-made maps, GIS data files and statistical summaries. Such an application typically uses hypertext markup language (HTML) to serve maps and statistics previously created by a GIS analyst. The static application delivers data fast because the server does not have to analyze data or create the maps and statistics; it just directs the user to the pre-made files. The downside is that static applications only work well 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 in recent years. A dynamic mapping application processes end-user submitted queries on the fly using the GIS data sets to produce maps, statistics and even subsets of the GIS data in real time. A dynamic Internet mapping application can be thought of as a customized on-line GIS, typically for non-GIS experts. This method is superior to static applications for GIS data that are continuously changing since changes made to the GIS data 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 the 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 require more robust server programming technologies such as ASP (Active Server Pages), CGI (Common Gateway Interface), 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 such as ESRI's ArcIMS (Internet Map Server – http://www.esri.com) that provide pre-developed, modifiable tools and templates to serve and query GIS data. Dynamic mapping applications also require higher-end servers than static applications. Depending on an Internet site's usage and the amount of data being served, multiple servers may be required for optimal performance.

Thanks to the recent widespread adoption of new technologies such as ASP.Net and XML (eXtensible Markup Language), creating GIS web services is also becoming popular and should become more common in conservation organizations in the near future. Web services are applications that allow approved remote servers 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) provides an excellent example of a GIS based web service where remote programmers can incorporate 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 evolving technology with implications to the future of conservation GIS is mobile wireless computing. It is becoming more affordable and common to connect to the Internet via wireless cell phones and computers. Combining these technologies with web services will allow field researchers to easily exchange data with their organization and others while in the field. For example, a researcher recording bird nesting site activity could upload his findings to update his organization's GIS daily while in the field, or he could download GIS data layers such as USGS quadrangle maps to his computer for integration with his GPS-integrated field-mapping program.

This section has provided a very general overview to Internet technologies for spatial wildlife and habitat data. 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 their pros and cons, and new technologies are constantly appearing that make existing technologies out of date. However, it is possible to surmise that rapid advancements in Internet server and programming technologies combined with steadily declining hardware costs are causing many conservation groups to focus their efforts on the dynamic mapping applications over static applications. Web services are also just starting to surface in conservation GIS and will likely become more utilized in the near future.

Combining these technologies with those of wireless mobile computing and GPS will present unlimited opportunities to field researchers.

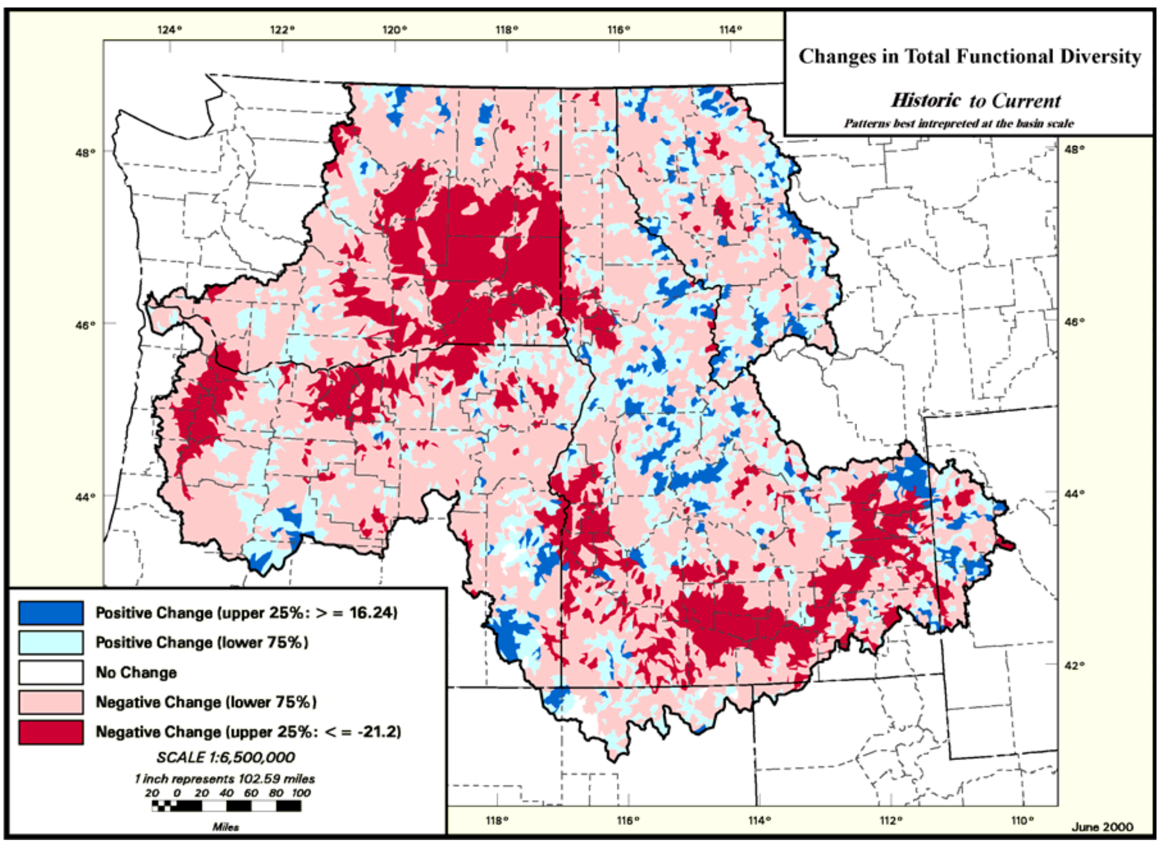
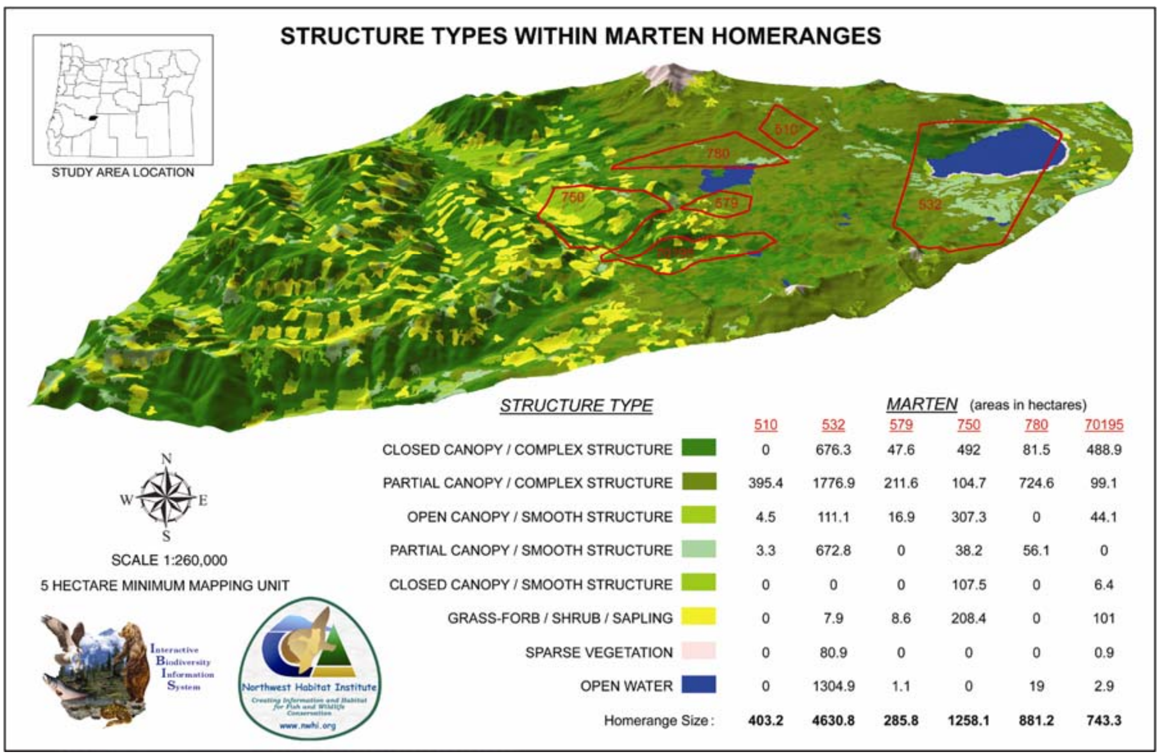


Figure 1. Using GIS, Marcot et al. (2002) depict the concept of Total Functional Diversity for the Columbia River Basin.



STRUCTURE TYPE	MARTEN (areas in hectares) 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
Homerange Size:	**403.2**	**4630.8**	**285.8**	**1258.1**	**881.2**	**743.3**

Figure 2: GIS allows an integration of data; as shown above American marten home ranges are overlaid on structural habitat conditions that are draped over topography. Source:

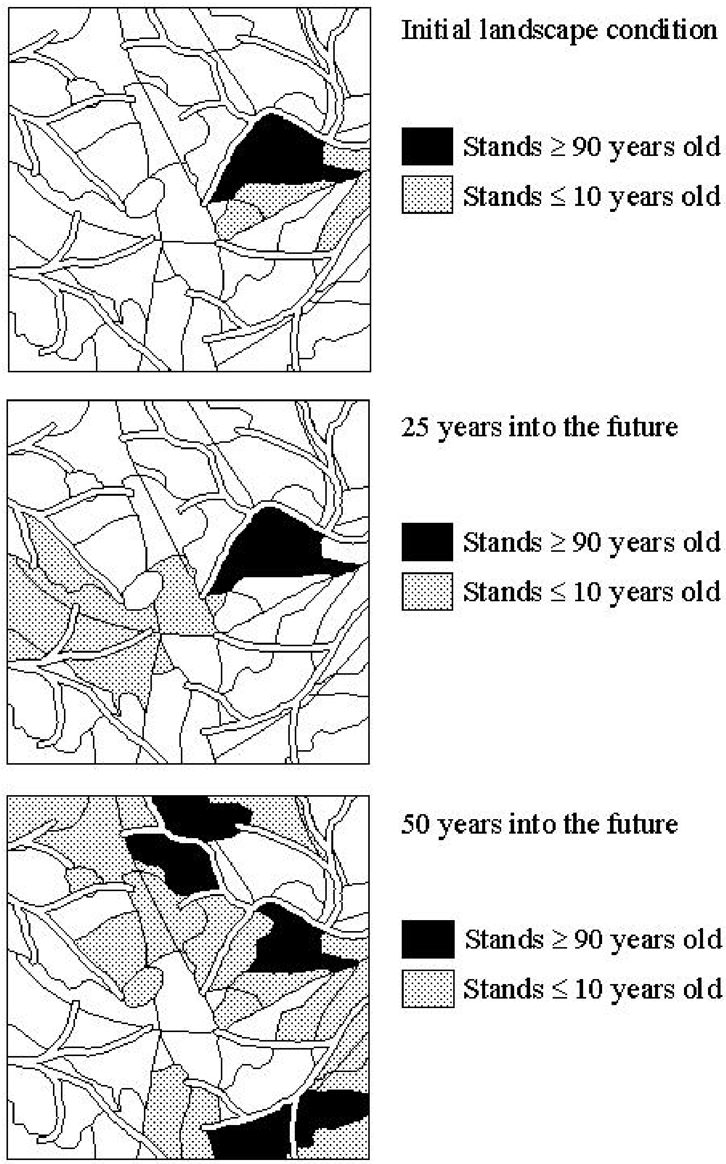

Initial landscape condition
Stands ≥ 90 years old
Stands ≤ 10 years old
25 years into the future
Stands ≥ 90 years old
Stands ≤ 10 years old
50 years into the future
Stands ≥ 90 years old
Stands ≤ 10 years old

Figure 3. Spatial arrangement of great gray owl habitat that consists of early successional stands and stands greater than 90 years old over a 50 year planning period.

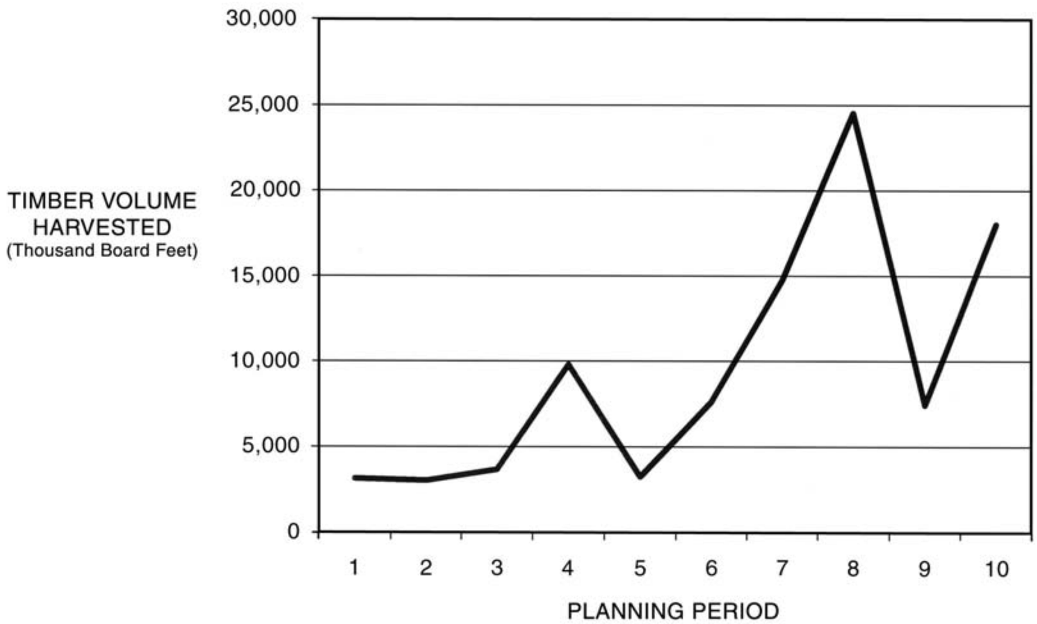


Figure 4. The amount of timber volume harvested over 50 years at 5-year planning increments.

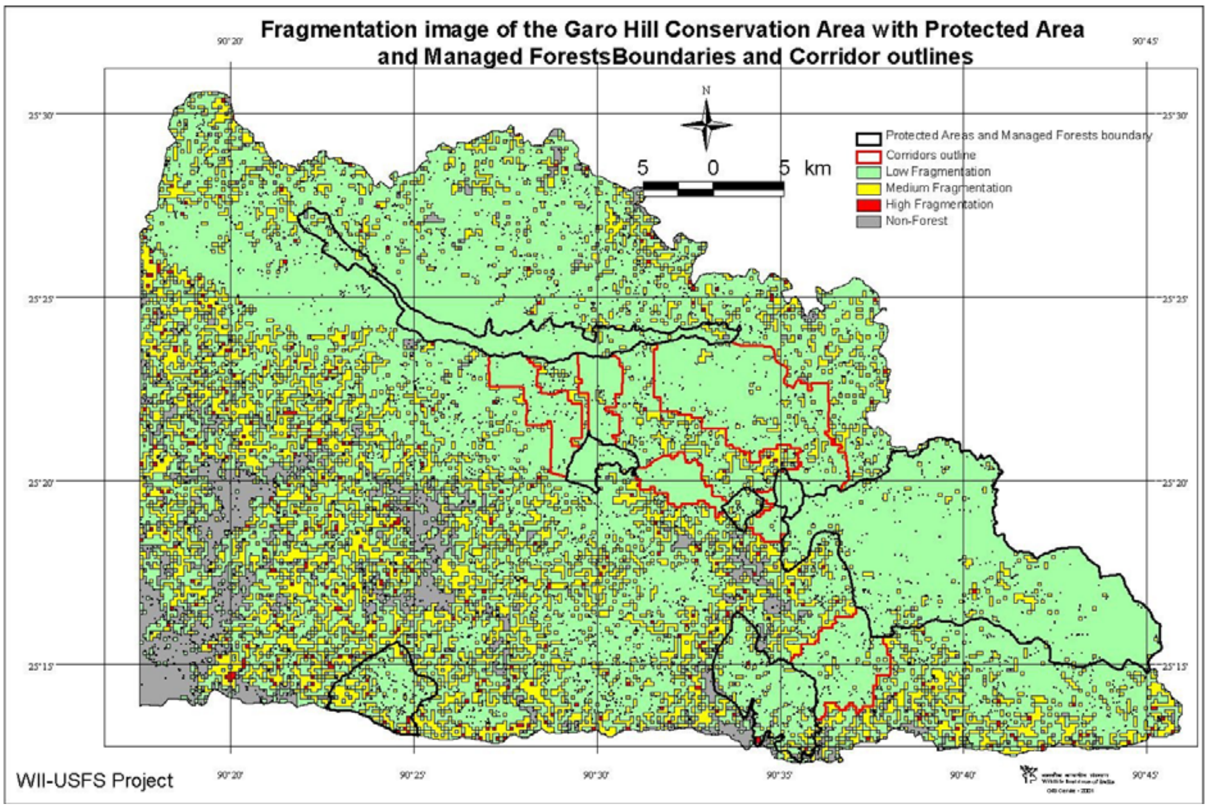


Figure 5. Use of GIS analysis of fragmentation of elephant habitat in Meghalaya, northeastern India to help delineate habitat corridors. Source: Marcot et al. (2002).

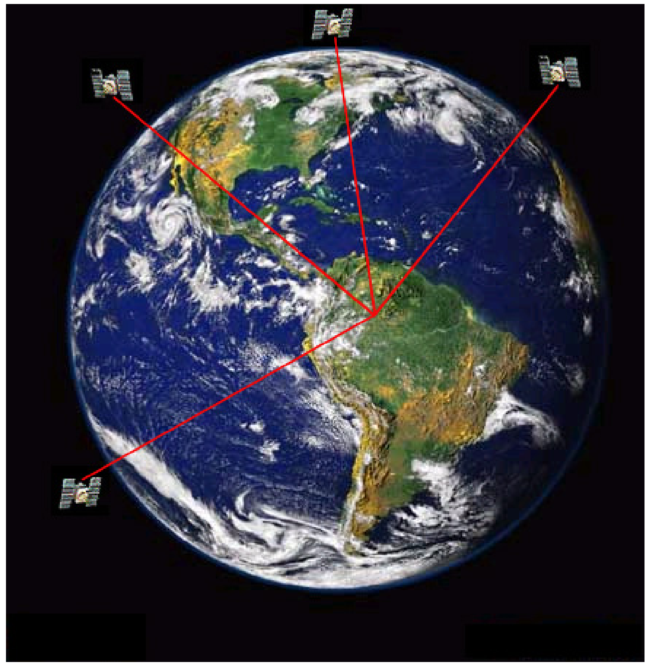


Figure 6. Three satellites are used for triangulation while the fourth satellite takes another measurement to check the other three.

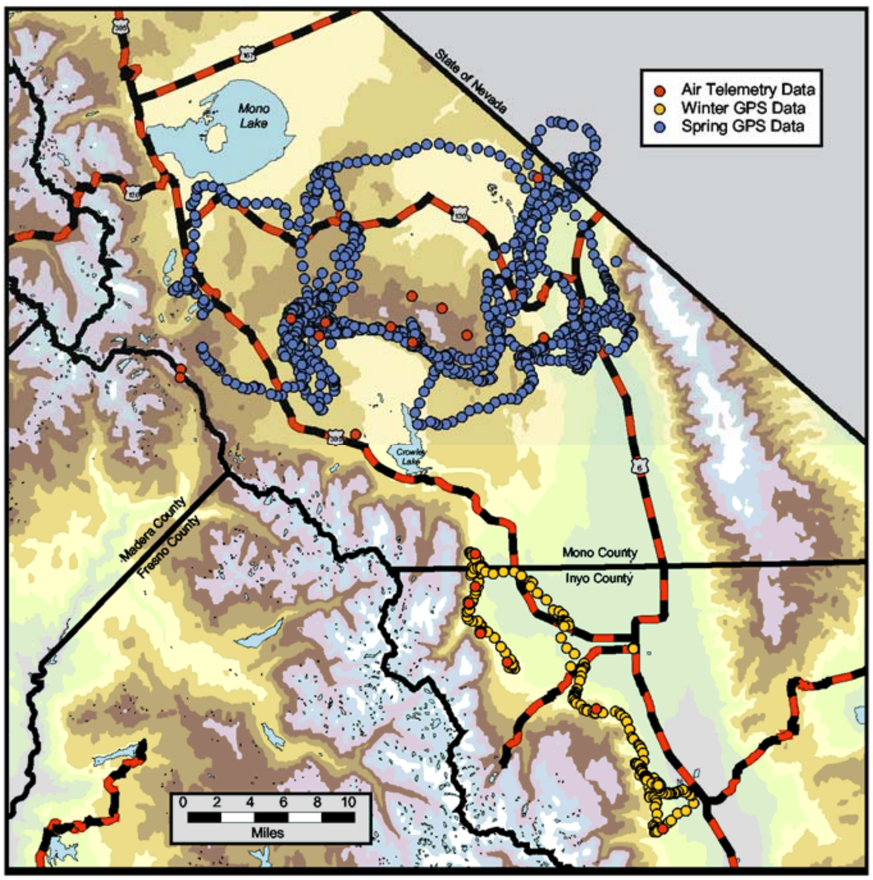


Figure 7. Mountain lion locations during the winter and spring as recorded from a GPS collar. Source: CA Dept Fish & Game/Vern Bleich, Becky Pierce, Tom Lupo, Steve Torres

Table 1. Problem formulation for a wildlife habitat goal related to complementary patches.

Goals:

To provide the greatest amount of great gray owl habitat over time.

Goal criteria:

Amount of land considered to be great gray owl habitat in each planning period.

Activities and decision variables:

Silvicultural activities include no harvest or regeneration harvest.

Decision variables are individual land units allocated to silvicultural activities.

Objective function:

Maximize the percent of land considered to be habitat for each species in each planning period.

$$\text{maximize}\left(\sum_{j=1}^{10}\sum_{i=1}^{n}\sum_{k=1}^{m} A_i H_{ijk}\right)/\left(\sum_{k=1}^{m} A_i\right)$$

Where: i = *land unit*

j = *time period*

k = *wildlife species*

A_i = *acres in land unit* i

H_{ijk} = *habitat (binary, 0 for no, 1 for yes) for species* k*, on land unit* i*, during planning period* j. *The determination of habitat is a function of average tree species age and size of contiguous habitat.*

Constraints:

Only one regeneration harvest can occur during the planning horizon.

$$\sum_{j=1}^{10} X_{ij} = 1 \quad \forall i$$

Where: X_{ij} = *binary (0 for no, 1 for yes) variable indicating a regeneration harvest on land unit* i *during planning period* j

Table 1. (cont.).

Timber volume produced must be above a minimum volume.

$$\sum_{j=1}^{10} A_i X_{ij} V_{ij} \geq \text{minimum harvest volume} \quad \forall j$$

Where: V_{ij} = *timber volume on land unit* i *during planning period* j

Habitat patches must be of certain sizes, and adjacent to each other.

H_{ijk} = *1 if size of contiguous habitat of ≥90-year-old forest ≥49.4 acres (≥20 ha), is adjacent to a contiguous area of ≤10-year-old forest that is ≥24.7 acres (≥10 ha) (or vice versa), otherwise* H_{ijk} *= 0. The determination of habitat is made using two area restriction models, similar to that described in Murray (1999), which are recursive functions that evaluate all adjacent units* y *to unit* i, *and all adjacent units* z *to unit* y, *and so on.*

Regeneration harvests must be equal to or smaller than a maximum size. An area restriction model is used to control the size of regeneration harvests (Murray 1999).

$$A_i X_{ij} + \sum_{y \in N_i \cup S_i} A_y X_{yj} \leq \text{maximum clearcut size}$$

Where: X_{yj} = *binary (0 for no, 1 for yes) variable indicating a regeneration harvest on land unit* y *during planning period* j

N_i = *set of land units adjacent to unit* i

S_i = *subset of regenerated land units containing all units adjacent to the* *neighbors of land unit* i*, and all land units adjacent to neighbors of neighbors, and so on.*

TABLE 2. Landsats 1-7 sensors spectral characteristics (Campbell 2002).

Sensor	Band	Spectral sensitivity
		Landsats 1 and 2
RBV	1	0.475-0.575 µm (green)
RBV	2	0.58-0.68 µm (red)
RBV	3	0.69-0.83 µm (near infrared)
MSS	4	0.5-0.6 µm (green)
MSS	5	0.6-0.7 µm (red)
MSS	6	0.7-0.8 µm (near infrared)
MSS	7	0.8-1.1 µm (near infrared)
		Landsat 3
RBV		0.5-0.75 µm (panchromatic response)
MSS	4	0.5-0.6 µm (green)
MSS	5	0.6-0.7 µm (red)
MSS	6	0.7-0.8 µm (near infrared)
MSS	7	0.8-1.1 µm (near infrared)
MSS	8	10.4-12.6 µm (far infrared)
		Landsat 4 and 5
TM	1	0.45-0.52 µm (blue-green)
TM	2	0.52-0.60 µm (green)
TM	3	0.63-0.69 µm (red)

TM	4	0.76-0.90 µm (near infrared)
TM	5	1.55-1.75 µm (mid infrared)
TM	6	10.4-12.5 µm (far infrared)
TM	7	2.08-2.35 µm (mid infrared)
MSS	1	0.5-0.6 µm (green)
MSS	2	0.6-0.7 µm (red)
MSS	3	0.7-0.8 µm (near infrared)
MSS	4	0.8-1.1 µm (near infrared)
	Landsat 7	
TM	1	0.45-0.52 µm (blue-green)
TM	2	0.52-0.60 µm (green)
TM	3	0.63-0.69 µm (red)
TM	4	0.70-0.90 µm (near infrared)
TM	5	1.55-1.75 µm (mid infrared)
TM	6.1 high gain	10.4-12.5 µm (far infrared)
TM	6.2 low gain	10.4-12.5 µm (far infrared)
TM	7	2.08-2.35 µm (mid infrared)
TM	8	0.52-0.90 µm (panchromatic)

Table 3. Willamette Valley example of an error matrix.

	2.1	2.2	2.3	2.4	2.5	2.6	3	9	20	21	21.3	22	30	31	39	463	463	476	476	505	505	506	510	510	512	512	999	1000	Total
2.1	80	12	11	1	3		1																						108
2.2	12	61	28	3	5																								109
2.3	2	5	85	4	12		2		2																				112
2.4	1	2	5	95	11		1		1																				116
2.5	2	2	2	3	100		1	1	3																				114
2.6				1	5	61	6													9									82
3	1					1	111									1											1		115
9	1	1	6	1				84	2				1							1			1		1				99
20	1		3	1	5		4		83	1		1				3							2		2				106
21							1			103	1	1				1							4						111
21.3											9						1						1						11
22	1	2	2	2	5				4			65				7													88
30	1	1	1		3			1	1				93	1		2													104
31									8			1	10	42		1			1										63
39				1	1							1	1		13														17
463	1		1		1					2						98	1					1	10						115
463																1	24						5	3				1	34
476	1		1		4				1							2		82		11		9	2	1	2				116
476																		1	30		8	7							46
505					1											4				92		19			1			1	118
505							1														38	10				2		7	58
506																		1				46	4	0	5				56
510					1				1	2						3				1		4	99		2				113
510																								30	1				31
512									1											4		6	1		101				113
512	1			1		1											2				2	4				35		2	48
999								2	2	1				1													53		59

1000									1																			56		57
																														2319
totals	105	86	145	113	157	63	128	88	110	109	10	69	105	44	13	123	28	84	31	118	48	106	129	34	115	37	54	67	2319	

Error Matrix Analysis

Overall accuracy = dia tot/tot points sampled 1869/2319 = 0.81

	2.1	2.2	2.3	2.4	2.5	2.6	3	9	20	21	21.3	22	30	31	39	463	463	476	476	505	505	506	510	510	512	512	999	1000	Total
dia totals	80	61	85	95	100	61	111	84	83	103	9	65	93	42	13	98	24	82	30	92	38	46	99	30	101	35	53	56	1869
col totals	105	86	145	113	157	63	128	88	110	109	10	69	105	44	13	123	28	84	31	118	48	106	129	34	115	37	54	67	2319
row totals	108	109	112	116	114	82	115	99	106	111	11	88	104	63	17	115	34	116	46	118	58	56	113	31	113	48	59	57	2319

producers accuracy = dia tot/col tot

0.76	0.71	0.59	0.84	0.64	0.97	0.87	0.95	0.75	0.94	0.9	0.94	0.89	0.95	1	0.8	0.86	0.98	0.97	0.78	0.79	0.43	0.77	0.88	0.88	0.95	0.98	0.84

users accuracy = dia tot/row tot

0.74	0.56	0.76	0.82	0.88	0.74	0.97	0.85	0.78	0.93	0.82	0.74	0.89	0.67	0.76	0.85	0.71	0.71	0.65	0.78	0.66	0.82	0.88	0.97	0.89	0.73	0.9	0.98

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