4

Measuring and monitoring land cover, land use, and vegetation characteristics

In terrestrial biomes, ecologists and conservation biologists commonly need to understand vegetation characteristics such as structure, primary productivity, and spatial distribution and extent. Fortunately, there are a number of airborne and satellite sensors capable of providing data from which you can derive this information.

We will begin this chapter with a discussion on mapping land cover and land use. This is followed by text on monitoring changes in land cover and concludes with a section on vegetation characteristics and how we can measure these using remotely sensed data. We provide a detailed example to illustrate the process of creating a land cover map from remotely sensed data to make management decisions for a protected area.

4.1 Land cover classification

This section provides an overview of land cover classification using remotely sensed data. We will describe different options for conducting land cover classification, including types of imagery, methods and algorithms, and classification schemes. Land cover mapping is not as difficult as it may appear, but you will need to make several decisions, choices, and compromises regarding image selection and analysis methods. Although it is beyond the scope of this chapter to provide details for all situations, after reading it you will be able to better assess your own needs and requirements. You will also learn the steps to carry out a land cover classification project while gaining an appreciation for the image classification process. That said, if you lack experience with land cover mapping, it always wise to seek appropriate training and, if possible, collaborate with someone who has land cover mapping experience (Section 2.3).

4.1.1 Land cover versus land use

Although the terms "land cover" and "land use" are sometimes used interchangeably they are different in important ways. Simply put, land cover is what covers the surface of the Earth and land use describes how people use the land (or water). Examples of land cover classes are: water, snow, grassland, deciduous forest, or bare soil. Land uses include: wildlife management area, agriculture, urban, or recreation. Some land cover maps include a mix of land cover and land use. For example, the map might have a "forest" (land cover) class and another class labeled "tree plantation" (land use). In a "pure" land cover map these would both be labeled "forest." Although there is nothing inherently wrong with mixing land cover and land use classes, it can sometimes lead to confusion. To avoid this confusion, it is important that each class on the map be clearly defined and distinct from other classes. One way to do this is to represent land cover using different colors while using different patterns or symbols overlaid on the map to represent land use.

Using image classification methods, ecologists and conservation biologists are able to identify and label land cover features to produce land cover maps from remotely sensed data. If you are able to place these land cover features into a use context you can create land use classes. For example, you can map forest as a land cover class but if you have information about how people use or manage the forest (usually obtained from field work) you can generate land use categories. Monitoring land cover and land use changes is an important tool to study whether and how policy affects the way people use natural resources (Thiha *et al.* 2007). These land use data are derived in different ways such as

- Map layers indicating how a particular area is managed such as wilderness, limited logging, or recreation provide direct information related to land use.
- Context of how one feature is situated in the landscape provides information about the likely use of that feature. For example, a forest area surrounded by an urban area is likely a park.
- Patterns of the land cover features often provide hints about how the land is used. For example, geometric shapes such as rectangles and circles can indicate agricultural fields.
- Sometimes the features themselves provide enough information to accurately label land use classes. For example, plantations tend to have a unique spectral response because all of the trees are the same age and the canopy is relatively even so plantations tend to look relatively smooth in texture on remotely sensed imagery.

The remainder of this section focuses on classifying land cover.

4.1.2 Options for output products

Land cover products can be grouped into two categories: classified maps and statistics. *Classified maps* are commonly used to represent land cover for a particular area. These maps group the landscape into discrete classes such as: forest, water, and grassland (see Fig. 3.18). One of the main advantages of this approach is that it provides mapped output in a format necessary for automated spatial analyses such as modeling and the calculation of landscape metrics. Statistics can be easily generated from these mapped products, so one effectively gets both output products when producing a classified map.

In spite of all of these advantages, classified maps have some disadvantages. For example, the classification process can be costly and time consuming. Classified maps also tend to be used for purposes for which they were not originally intended, often assuming that the map is more accurate than it is. A common example of this is using a land cover map created from satellite imagery that has much coarser resolution than necessary for the intended application (i.e., using a global 1 km resolution land cover map for a small protected area).

During the early years of satellite remote sensing, providing *statistics* summarizing the area covered by each land cover class offered the most common approach to land cover analysis simply because creating classified maps for large areas required too much computer power. To create change statistics you would develop a sampling strategy whereby small portions of the image are classified and, using statistics, generate estimates for the various cover types for the entire study area.

The primary disadvantage to the statistics-only approach is that there is no mapped output. In this age of spatial analysis, providing a visual representation is often a project requirement.

4.1.3 Comparing land cover maps with image photoproducts

Before we address the topic of land cover mapping we should first understand how a classified map differs from a remotely sensed image. A visual representation of a satellite image can be thought of as a photograph of the Earth's surface acquired from space. Methods to visually interpret satellite images are very similar to methods developed to interpret aerial photographs over 100 years ago. Using visual cues, such as tone, texture, shape, pattern, and relationships to other objects, an observer can identify many features in an image (see Section 3.5.1 and Appendix 5).

When using a land cover map it is important to keep in mind that it is an abstraction of actual land cover. When we classify a satellite image, thematic classes replace the visual cues that exist in the original image. For example, the subtle changes throughout a forest that can be seen in an image photo are replaced by a single color representing a particular feature such as forest (Fig. 3.18). Another feature of most land cover maps is that they portray different land cover classes as discrete entities with well-defined boundaries. In many cases, however, the actual change from one land cover type to another is gradual and this is easily visualized using the original image data. Defining a discrete boundary between land cover that transitions from one cover type to another in a continuous fashion often results in a somewhat arbitrary line drawn between those different classes.

Therefore, when would you choose to use the original image and when a classified map? First, in many quantitative studies the preferred data product would be a classified map in a digital format (as opposed to a hardcopy or paper format). One clear case for using classified data is in modeling (Chapter 14). When modeling, the algorithm needs to know the value of a particular parameter at a particular location, and that information is available in a classified image. For more qualitative studies, however, image representations of the data could be the product of choice. Examples of qualitative applications where image photo products might be preferred to land cover maps include:

- Planning protected area limits.
- Planning field work.
- Getting a broad-picture view of an area to understand land cover types and patterns.

4.1.4 Getting started

A good place to start is to define explicitly why you need to create a map and how will it be used. Reading this section will provide sufficient information regarding the factors that you will need to consider for a needs assessment. You should write down the results of a needs assessment for future reference. It will become obvious that there are several decisions that you need to make based upon how you will use the map. Accordingly, these decisions will determine many of your choices throughout the classification process. The next several sections detail the steps of a land cover mapping project.

4.1.5 Requirements for creating a land cover classification map

Creating a land cover map using remotely sensed imagery necessitates access to suitable imagery. There are several choices available and the process of selecting the appropriate imagery is described in Section 4.1.8.

You will also need some way to visualize and process the imagery. If the imagery is in a printed form, then viewing it is relatively straightforward and the classification process is essentially limited to visual interpretation methods. However, if the imagery is in digital form, you will need software to view and process the imagery. Software required for classifying imagery can range in price from free to tens of thousands of dollars (Appendix 2). There are several options available when using digital imagery and these are detailed in Section 3.5.2.

It is easy to focus on the skills needed to operate a particular piece of remote sensing software. However, the most important skill in our experience is the ability to accurately associate the features that can be seen in an image with what is on the ground. This ability comes from experience (Section 3.5.1 and Appendix 5).

Lastly, whether you are just learning image classification or you have been through some formal training such as workshops or university classes, it is always a good idea to get some feedback from experienced colleagues. Discussing your plan of action and periodically showing your progress to other remote-sensing practitioners is very helpful. They can sometimes suggest refinements and offer other options that will help improve the land cover map.

4.1.6 Define the study area

Once you identify how you will use the map you need to define the region to map. This can be a fairly easy task. When delineating the area to be mapped it might be important to include an area adjacent to the primary study area. This could be done to better understand the transition to the area outside of the study area. An easy way to do this is to create a buffer around the primary study area so you include adjacent areas (Fig. 4.1). You can create buffers using common geographic information system (GIS) software or image-processing software.

In some cases it can be difficult to reach consensus among project participants about the study area. For example, you might find that adding a small portion to a study area will involve the purchase of additional imagery and therefore increase the required resources to conduct the classification. After discussing

Fig. 4.1 We defined the scope of a land cover analysis of Bach Ma National Park in central Vietnam by including a 1.5 km buffer (transparent strip). The inside line of this buffer is the boundary for the park. By including the buffer in the land cover analysis of the protected area some of the land surrounding the park is included in the study (Landsat ETM+ image; path 125; row 49; April 21, 2003). Credit: Ned Horning, American Museum of Natural History's Center for Biodiversity and Conservation.

this situation with project participants you may decide that the additional cost to include the small portion of the study area cannot be justified and the study area will have to be modified.

4.1.7 Defining a classification scheme

A classification scheme effectively defines the legend that will be used for the final map. For example, will the map show forest and non-forest or will it have several or even dozens of different categories? Should the final map categories represent land cover or perhaps something else such as habitat or conservation importance? The way in which the map will be used, and some practical realities, will dictate the content of the classification scheme.

There are a large number of standardized classification schemes used for land use and land cover maps throughout the world. Some of the more common systems are listed in Table 4.1. An important point to remember is that no matter what classification scheme is selected, each class must be well defined and documented. For example, if you have a class called "Forest," you need to specify what constitutes a forest. Do the trees need to be a certain height? How dense do the trees or their canopies have to be? With this information it is possible for the user of the final map to clearly know what the different classes represent.

When choosing an appropriate classification scheme you should decide if compatibility with existing schemes is necessary or desirable. Some advantages of using an existing system are that the classes are already defined and the map you produce can be easily compared with other maps using the same system.

The Food and Agriculture Organization (FAO) of the United Nations developed the Land Cover Classification System (LCCS), which is gaining in popularity among land cover mapping projects around the world. The LCCS is supported by extensive documentation and a software tool that is freely available

Table 4.1 Examples of major land cover classification schemes designed for use with remotely sensed data.

Classification name	URL	Designed for sensor
Anderson	http://landcover.usgs.gov/pdf/anderson.pdf	Landsat and aerial photography
United States National Land Cover Data	http://eros.usgs.gov/products/landcover/nlcd.html	Landsat
FAO Land Cover Classification System	http://www.africover.org/LCCS.htm	N/A
Geocover-LC	http://www.mdafederal.com/geocover/geocoverlc	Landsat
Global Land Cover (IGBP DISCover/MOD12)	http://edcsns17.cr.usgs.gov/glcc/	AVHRR, MODIS

from FAO. An excerpt from the Summary of the LCCS User Manual (Gregorio and Jansen 2000) states:

> The Land Cover Classification System (LCCS) is a comprehensive, standardized *a priori* classification system, designed to meet specific user requirements, and created for mapping exercises, independent of the scale or means used to map. Any land cover identified anywhere in the world can be readily accommodated. The classification uses a set of independent diagnostic criteria that allow correlation with existing classifications and legends.

Defining mapping classes is often an iterative process. You must strike a balance between the classes you want, based on the map's purpose, and the classes that you can accurately and economically delimit. In general, greater detail translates to greater cost in time and money. A good rule of thumb is to select the minimum number of classes that are practical (Section 2.2.2).

When selecting classes, you can use a hierarchical or nonhierarchical approach. In a hierarchical approach, classes are nested such that major classes are broken into subclasses and these subclasses can further be broken into more detail. The advantage of such a system is that you can easily generalize the classes and it is easy to adapt to various scales (in general, the finer the map scale, the more detailed the hierarchy will be). A nonhierarchical approach, however, is designed for a specific purpose with a specific scale in mind. The advantage of a nonhierarchical system is that you can modify it to suit a specific application. In other words, you can more easily customize it for specific project goals since it can include a mix of detailed and generalized land cover classes.

When defining classes, you must decide how to classify mixed features such as transition and mosaic classes where multiple land cover types occur together. One approach is to explicitly define these classes as mixed or transition and the other is to ignore the fact that classes are mixed and define classes by the most common feature on the ground within a delineated unit. When deciding which approach to use in representing mixed features, you must take into account the nature of the features being mapped and how important mixed classes are relative to the intended use of the map. You should clearly document whichever method is used.

Another point that has to be considered with the classification scheme is the spatial detail that you will want in your map. A minimum mapping unit defines the smallest area that is delineated on a map. For instance if the minimum mapping unit is 1 ha, then any feature smaller than 1 ha would not be delineated as a unique feature. Instead it would be incorporated into another feature. Minimum mapping units can vary from class to class, so more important or rare classes would have a smaller minimum mapping unit to ensure that they are not lost as a result of inclusion in another class. In some cases no minimum mapping unit is used and all recognizable features are identified. No matter the approach, it is important that it meets the requirements of the needs assessment, is applied consistently, and is well documented. The level of detail that you can extract when creating a land cover map depends largely on the type of imagery that you use (Section 2.1.1).

4.1.8 Selecting imagery

Now that you have defined the classes you want to map, you will need to select imagery that will allow you to accurately define these classes. Selecting appropriate satellite imagery is, more often than not, limited by data availability and project budget. If the project budget is small, you may be restricted to using free or inexpensive imagery, which in turn affects the level of information that you can extract for the map. Ultimately, this may require that the project goals be adjusted to reflect the practical limitations.

The spatial detail of the information you need will dictate the required resolution of the imagery and this will significantly limit the list of possible image types that can be used. For example, if you were interested in identifying individual trees you would need fine-resolution satellite images or aerial photographs. If, at the other extreme, you wanted to create a global land cover map, you would look for imagery with a much coarser resolution. The selection of an appropriate image resolution is somewhat of an art and experience will improve your ability to know what can be reliably mapped using different image resolutions. One way to get a sense for the level of detail you can expect from a particular image type is to display the image on a computer monitor and zoom and roam around the image to see how well you can identify individual features. In general, if you can see your feature of interest on the screen, there is a good chance automated methods will properly classify it.

4.1.9 Image preprocessing

Preprocessing can be divided into two categories, radiometric and geometric (see Section 3.4 for more details on radiometric and geometric preprocessing). When conducting automated classification, improving the radiometric and geometric qualities of the data tends to improve classification accuracy since you are essentially reducing the noise in the image. With visual interpretation, however, this is not always the case. For example, in mountain environments there is often one side of a mountain that is brightly lit while the other side is in shadow. If not corrected, this effect will introduce problems for automated classification since the same land cover will look very different. However, with visual interpretation this illumination effect can actually help since it tends to accentuate three-dimensional features (Fig. 4.2). Moreover, a trained analyst is able to accurately classify and identify the vegetation even though the shadows and topography make the vegetation features appear like two distinct classes.

Geometric correction typically involves warping an image to match another image or some other reference data set (Section 3.4.3). Whenever an image is warped a resampling of the image pixels takes place, which degrades the original data to some degree (see Box 2.1). This has more of an influence when applying

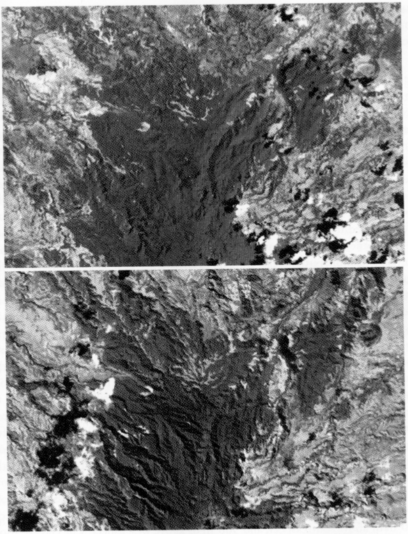


Fig. 4.2 Shadows can help improve the interpretability of an image. The top image of the northern part of Madagascar was acquired when the sun was high in the sky in the southern hemisphere (Landsat ETM+; path 159; row 69; December 4, 1999). The bottom image was acquired over the same area when the sun was significantly lower in the sky and therefore shadows are more pronounced (Landsat TM; path 159; row 69; June 25, 1984). You can see much more detail in the terrain in the lower image. Credit: Ned Horning, American Museum of Natural History's Center for Biodiversity and Conservation.

automated methods since the individual pixel values are modified. This effect may or may not be significant, depending on the application, but in general it is best to minimize the processing steps that involve resampling image pixels.

4.1.10 Ancillary data

In addition to satellite or aerial imagery, you can use other data to increase the accuracy of the classification. Some possible ancillary data types are digital elevation models (DEMs) and their derived data sets (slope and aspect), climate data such as precipitation and temperature, and vector overlays such as roads, rivers, and human population density. If there is a factor that affects the distribution of land cover that exists in a mapped form, you should try to incorporate it into the classification process. For example, DEMs often supplement satellite data when mapping land cover since specific vegetation classes are often limited to specific elevations or aspects.

Sometimes we might be aware of an attribute that we want to incorporate into the classification but there is no available data set that is appropriate for the study. For example, rainfall affects vegetation distribution but many rainfall data sets are too coarse to be useful in classifying vegetation. As time goes on, more of these environmental layers will be improved so that you can use them to map vegetation more accurately and at finer scales (Chapter 8).

Incorporating ancillary data into the classification process is not always easy. Some of the classification methods discussed in Section 3.5.2 allow the incorporation of assorted data sets but others are more restrictive. For the more restrictive methods, there are still some ways to utilize ancillary data. One is to use these data to stratify the study area into regions based on one or more environmental variables. We might use a DEM to create unique strata for elevation, slope, and aspect ranges. For example, we could create two elevation categories (below 500 m and 500 m or above) and four aspect categories (north, east, south, and west) and from these create the following eight strata: below 500 m north aspect, below 500 m east aspect, below 500 m south aspect, below 500 m west aspect, 500 m or above north aspect, 500 m or above east aspect, 500 m or above south aspect, and 500 m or above west aspect. The classification can then be carried out within each of the individual strata. Defining strata will generally have a positive effect on the accuracy of a classification product.

4.1.11 Classification methods

Image classification is covered in detail in Section 3.5.2. In the case of land cover classification, image pixels are assigned to categories (classes) that comprise different types of land cover defined by the classification scheme being implemented. There are dozens, if not hundreds, of classification methods you can use to group image pixels into meaningful categories. Unfortunately, there is not a single "best" approach to image classification. The choice you make depends on the algorithms available to you given the image-processing software you use, the data you have available, and your familiarity and experience with the different methods.

4.1.12 Field validation

Although land cover maps are often made without visiting the area in the image, there are good reasons why you should visit the area. The two primary reasons you would want to visit the area being mapped are to collect data to train the algorithm or the interpreter, and to collect data to evaluate the land cover map and estimate the accuracy of the individual classes, a process called validation. At a minimum, these data can be collected in one trip but often times two or more trips are preferred so that you can systematically collect validation information using a sampling design based on the classification results.

You must georeference your field data so that the point where you collected the data can be located on the imagery. Global positioning system (GPS) receivers are commonly used to record this location information. The type of information collected can range from detailed notes describing a site to a photograph of the site. Some of the detailed information that you can record includes type of vegetation, crown closure, slope, aspect, soil type, and other biological or physical characteristics that are important to identify the land cover type. If you take photographs it is a good idea to record the direction the camera was pointed and to make notes about the area to supplement the content in the photograph. For example, you could add information about species composition, tree height, and possibly land use.

When land cover maps are created without using field data from the region of interest it is difficult to interpret the accuracy of the final land cover map. An analyst with significant experience may be able to produce a land cover map of high quality but without validating information the true accuracy of the image classification quality is not known.

4.1.13 Accuracy assessment

In the needs assessment you should give some thought to the accuracy of the final map. The sampling statistics for this process are fairly straightforward but the practical issues such as limited access to the study area, insufficient funds to visit all of the sites, and a lack of time tend to impose limitations that must be accommodated in the sampling design. Dealing with this less than ideal situation may necessitate some creative solutions that require an understanding of statistics that are beyond the expertise of the image analyst. See Section 2.2 for more information about accuracy assessment.

4.1.14 Using the completed map

Classified maps are used for a host of quantitative analysis applications such as species or landscape modeling, fragmentation analysis, and setting conservation priority areas. They can also be used as visual aids in a presentation or as a layer in a GIS. No matter how a classified map is used, it is critical to have some information on the accuracy of the map. This information can come from a carefully planned accuracy assessment or some less rigorous qualitative methods but the source of the accuracy value should also be known. It is important to keep in mind that a classified map is only an approximate representation of the features on the ground. The accuracy of this representation can greatly affect the results of any quantitative analysis.

Another important characteristic of a classified map is spatial scale. This is especially important when using a land cover map to calculate landscape metrics. A coarse-scale land cover map will produce very different results than a finer-scale map when calculating most landscape metrics (Chapter 10).

4.2 Monitoring land cover change

Beyond studies of the fragmentation of target habitats, conservation biologists have an increasing need to evaluate the effects of change in the surrounding matrix of terrestrial or aquatic habitats. This section focuses specifically on issues relating to measuring and monitoring changes in land cover over time. We will present a number of different change detection approaches along with their strengths and weaknesses.

Remote sensing methods can be used to monitor changes within and between many different vegetation cover types such as grass, shrubs, and woodlands. This section uses forest monitoring to illustrate the fundamentals of remote sensing-based monitoring but similar approaches and issues are relevant for monitoring other land cover types.

Throughout this section, we refer to an early (older) and late (more recent) date image. Limiting change detection to two images is done to keep the examples simple, but in actual projects you can use more than two dates. After reading this section you will have sufficient information to understand how land cover change mapping works, and what approaches are available to answer your specific questions.

4.2.1 Reasons for mapping land cover change

Before starting a land cover change project it is important to define the objectives of the analysis. Reviewing these objectives will provide insight into what methods are necessary to achieve them. This seemingly obvious step is often skipped simply because someone decides that creating a land cover change map is a good idea. The person may not know why it is a good idea but it seems like the right thing to do.

Therefore, what are some reasons for conducting a land cover change analysis? Here is a list of common objectives:

- Identify areas of deforestation/reforestation.
- Identify or quantify seasonal patterns of change.

- Monitor growth of urban or rural populations.
- Predict future change based on past change.
- Provide input into climate or carbon budget models.
- Monitor changes in species habitat.
- Monitor changes in agriculture patterns.

4.2.2 Monitoring changes in forest cover

A very common type of change detection is monitoring changes in forest cover over time. This typically involves comparing two dates using one of the methods described below and noting where forests have been cleared or where they have grown back (Lu *et al.* 2004). The detection of a change from a dense forest to a cleared area is relatively straightforward and can be done with high accuracy (Section 2.2.2). We are often interested in other types of forest cover change such as selective logging, differentiation between young secondary and more mature forests, and changes in areas with low tree density such as woodlands. Monitoring these less dramatic types of forest cover change can be difficult largely because the changes are not abrupt, as they are with clear-cutting, but occur over a gradient. Determining where along that gradient change can be reliably detected is far from straightforward.

Although some progress is being made (Asner *et al.* 2005), monitoring forest degradation such as selective logging is still impractical at regional and global scales. High-resolution imagery that can detect gaps created in the canopy when a tree is removed can be used to detect some selective logging but in many dense forests these gaps in the canopy will close over a period of a few years.

Separating young secondary forests from more mature forests can also be difficult. Over time a newly planted forest will begin to be indistinguishable from a more mature forest when viewed on remotely sensed imagery. The length of time it takes for a young forest to resemble an older forest on remotely sensed imagery depends on a number of factors including the local environment, the type of forest, and type of remotely sensed data being used. One study demonstrated that you cannot distinguish between secondary and primary moist tropical forests 14 years after the primary forest was cut using Landsat Thematic Mapper data (Steininger 1996).

Monitoring changes in tree cover in an area with sparse trees can be troublesome. The lower the tree density the more the area will appear like the surrounding vegetation, often grassland or shrubs. In areas with low tree density the change in contrast after trees have been removed may not be great enough to detect.

4.2.3 Visual methods for monitoring land cover change

All too often we shun a simple visual approach to monitoring changes in land cover. With this approach two images from different dates are viewed simultaneously either by overlaying bands from the different dates (Fig. 4.3), displaying the images side by side, or rapidly switching between images acquired at different times using flicker or swipe options offered in many image-processing software products (Fig. 4.4). Creating a red, green, blue (RGB) color composite by

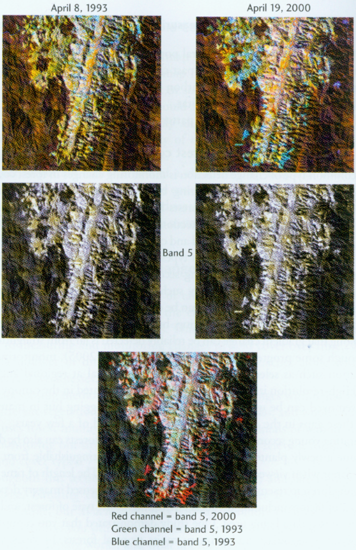


Fig. 4.3 A way to quickly and easily visualize change is to create a color image using bands from images acquired on two different dates. The top row images are two-color composites of Landsat images from the same month in 1993 and 2000. The second row shows band 5 (mid-infrared) from these images. The multitemporal image at the bottom is a color composite image created using the two mid-infrared images from the two dates by assigning the band 5 image from 2000 to the red channel and the band 5 image from 1993 to the green and blue channels of the color composite. In the multitemporal image dark red patches indicate areas that have been converted from forest to non-forest. Placing this image next to the color composites in the top row provides a quick overview of changes in land cover over time. The same Landsat images will also be used in Figs. 4.4–4.6, 4.8, and 4.9 (path 158; row 72; TM on April 8, 1993; ETM+ on April 19, 2000). Credit: Ned Horning, American Museum of Natural History's Center for Biodiversity and Conservation.

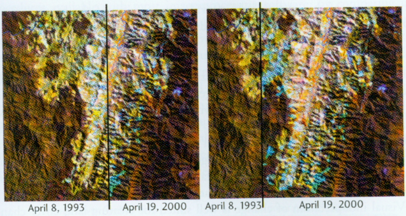


Fig. 4.4 Another visual technique is to flicker or swipe between images acquired on two different dates. We used a swipe function that is common in image-processing software to show changes between the two images in Fig. 4.3. With a swipe tool you superimpose one image over the other, and one date is displayed to the left of the swipe line (the black vertical line), while the other image is displayed to the right of the swipe line. By moving the line back and forth you can control the amount of each image displayed and the changes between the images become apparent. Credit: Ned Horning, American Museum of Natural History's Center for Biodiversity and Conservation.

mixing bands from images acquired on different dates is an excellent way to visualize change (Fig. 4.3). One way to do this with Landsat ETM+ imagery is to select band 5 (mid-infrared, 1.55–1.75 m) from the more recent date for the red output channel and band 5 from the older date for the green and blue output channels. When the image is displayed, areas that have undergone change will be displayed as different colors. For example, an area that was forest in the early date and cleared in the late date would appear red. Another band that is often used for this method is Landsat ETM+ band 3 (red, 0.63–0.69 m) although this tends to be noisier than band 5.

The primary advantage to visually comparing two images is that it can be done immediately after you acquire the data. Another advantage is that you can get a better sense of the actual landscape since you are effectively looking at a picture of the landscape rather than a map of discrete categories as in a classified map.

The downside to this approach is that it does not produce a quantitative product. That said, before this method is put to the side, it is important to ask yourself if a visual product can meet your needs.

4.2.4 Selecting a change detection method

There are dozens of ways to create land cover change maps and it is beyond the scope of this section to provide sufficient details to implement each one of these.

The purpose of this section is to provide an overview of the more common options (Mas 1999) and describe the advantages and limitations of each.

4.2.4.1 On-screen digitizing/editing

On-screen digitizing, or heads-up digitizing as it is sometimes called, is a manual method for creating land cover change maps relying on visual interpretation (Fig. 4.5). It involves an analyst drawing polygons that represent land cover change classes on a computer screen. This is the most subjective of the approaches but the human brain is still better at classifying the vast array of landscape features than a computer algorithm. The downside is that this approach is more susceptible to operator fatigue and bias than automated methods and tends to be slower in complex or large areas.

Visual interpretation of change is well suited for creating land cover change maps through the process of editing an existing land cover map. In this scenario, you create a land cover map for one time period (either the early date or the late date) using your method of choice. Validate this baseline map to assure that the quality is acceptable. Next, edit this land cover map using image editing

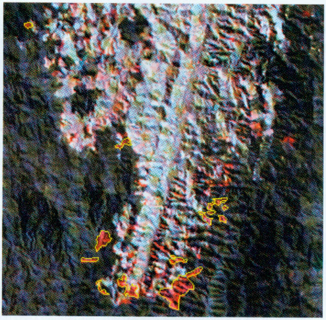


Fig. 4.5 Changes in land cover can also be mapped using manual hand digitization methods. To do this, it is helpful to display color composite images of each date as well as a color composite change image such as the one in Fig. 4.3. In this image an analyst has delineated a number of polygons that appear to be areas of deforestation. Credit: Ned Horning, American Museum of Natural History's Center for Biodiversity and Conservation.

procedures available with most image-processing software, by comparing the land cover map with both the image used to create the land cover map and the complementary image (if the land cover map represents the late date then the complementary image would be the early date satellite image). By comparing these three products, one can visually note areas that have changed from one cover type to another and edit the land cover map to represent this other time period. During the process of interpreting change, the analyst will occasionally find errors in the original land cover map and these errors can be corrected. This is an additional benefit of using a visual editing process. Updating or editing a land cover map to monitor changes in vegetation over time can often be done for a fraction of the cost required to produce the initial baseline map.

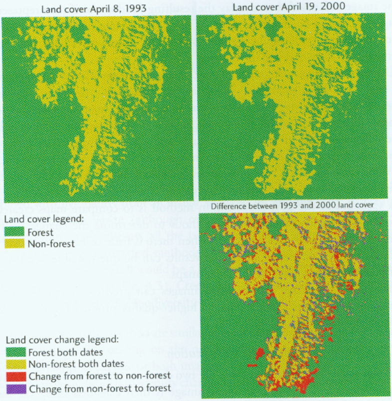


Fig. 4.6 A common and intuitive way to compare land cover from two different dates is to overlay the two land cover maps, a process termed post-classification change detection. The two independently classified land cover maps are illustrated in the top row and the result of overlaying them is shown in the bottom image. We performed classifications on the same Landsat images shown in Figs. 4.3–4.5. Credit: Ned Horning, American Museum of Natural History's Center for Biodiversity and Conservation.

4.2.4.2 Comparing two classified images (post-classification comparison)

This is likely the most common and intuitive change detection method. However, it rarely produces the most accurate results. In this method, you produce a land cover map for each of the two dates and then compare these two land cover maps using simple image math to determine the land cover change map (Fig. 4.6).

Logically, this approach makes a lot of sense and it has the advantage of directly providing land cover maps for the individual dates in addition to the change in land cover between the two dates. The problem is that the errors from each of the individual land cover maps are incorporated (they are cumulative) into the final change product, which makes the error of the final map significantly greater than that of the individual land cover maps.

One way to illustrate this multiplication of errors problem is to classify the same image twice and then overlay the resulting products as if they represented imagery acquired on different dates. When these images are overlaid, you will perceive changes in the land cover even though the exact same image was used to represent the early and late time period.

One instance where this method may be appropriate is when the images from the two dates have substantial variation not related to changes in vegetation cover. When this is the case some of the other change methods would tend to lump together the non-land cover changes with those related to changes in land cover. For example, if you are studying land cover change in an area with deciduous vegetation and one of the images was acquired with leaves on and the other with leaves off, the other change methods might have a difficult time differentiating between land cover change and changes due to phenology.

A variation of the post-classification method is to compare maps created at different times and using different methods to determine the changes in land cover over time. With this approach, when there is little or no control over the methods used to create the maps, the results can be questionable because you cannot assess the accuracy of the input maps.

Although comparing two classified images can produce acceptable results, alternative approaches often produce a higher-quality product for a given level of effort and resources.

4.2.4.3 Multi-date composite classification

With this approach the images from the two dates are combined into one multi-temporal image. This multi-temporal image is then classified using the automated classification method of choice such as those outlined in the land cover mapping section above. For example, it is common to combine Landsat TM bands 1–5 from the two dates to create a 10-band image containing all of the bands from the two dates (Fig. 4.7). This 10-band image is then used as input into the classification algorithm. This approach has the advantage of directly outputting the change classes, which effectively reduces the classification error when compared to the post-classification method described earlier. Although this method does not directly output land cover maps for the individual date, this information can be derived from the change classes.

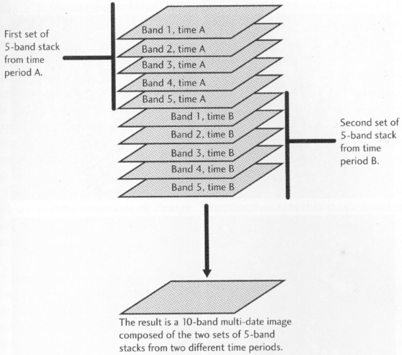


Fig. 4.7 Images from multiple dates can be combined to create a single, multi-date image. In this figure five bands from an image acquired on one date are combined with five bands from an image acquired on another date to create a 10-band multi-date image (although only three of these bands can ever be visualized in an image display, all the bands in the multi-date image can then be processed using automated methods similar to those used to create land cover maps, except the result would be a land cover change map (Landsat images are the same as shown in Fig. 4.3). Credit: Ned Horning, American Museum of Natural History's Center for Biodiversity and Conservation.

The limitations to this method are similar to those associated with automated land cover classification. Depending on the quality of the two images there may be sufficient variation across one or both images not related to changes in land cover. This would make it difficult to identify change consistently with reasonable accuracy.

4.2.4.4 Image math

When using an image math approach you can work with either individual bands or more commonly single-band image products such as vegetation indices or individual image bands from different dates. You then compare the single-band images from each of the two dates by subtracting or differencing them. Then you analyze the resulting image to determine the range of values that represent a change in land cover from one date to the next (Fig. 4.8). One approach is to

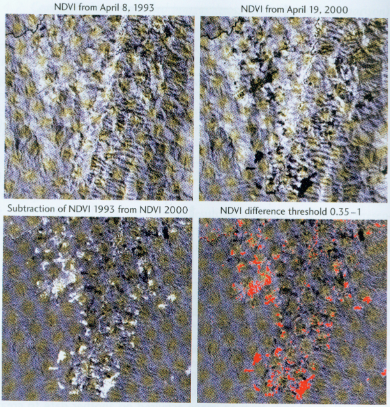


Fig. 4.8 Band math—subtracting the pixel values of one image from another—can give a quick overview of areas that have undergone change. These images show calculated Normalized Difference Vegetation Indices (NDVIs) for the two Landsat images shown in Fig. 4.3 (*top*). Then we calculated the difference between the two NDVI values for each pixel. The image resulting from the subtraction is in the lower left. When NDVI values are displayed, brighter pixels indicate the presence of vegetation. In the difference image, bright areas had high-NDVI values in the 1993 image and lower values in 2000. The image in the lower right highlights those pixels that had a significant drop in NDVI value between 1993 and 2000. These highlighted values can be used as a mask to restrict future processing to areas where a significant reduction in NDVI has been noted. As you can see, some of the highlighted areas did not change from forest to non-forest but from grass to cleared or burned land. This is because the change in NDVI value from grass to cleared or burned land is quite significant. NDVI highlights vegetation changes but does not discriminate between specific land cover types. Credit Ned Horning, American Museum of Natural History's Center for Biodiversity and Conservation.

create a Normalized Difference Vegetation Index (NDVI) (Section 4.3.1.1) image for each date and then subtract the NDVI images from each other to determine which pixels represent actual changes in land cover. Large differences in NDVI values between the two images would suggest that there has been a change in land cover between the two dates. When using this approach to map changes in land cover you must determine a threshold of change. The advantage to this approach is that it is easy and fast. The primary disadvantage is that while the output highlights areas that have experienced an increase or decrease in vegetation cover, it does not provide detailed information about what the land cover changed from or to. It is also sensitive to changes not related to land cover such as changes due to seasonality and changes in atmospheric conditions (clouds and haze).

This method is often used to create a mask (Fig. 4.8) highlighting areas that have undergone some sort of change. You can then use this mask with other methods to limit the analysis only to those areas that are suspected of undergoing actual land cover change.

4.2.4.5 *Spectral change vectors*

In spectral change vector analysis, changes in vegetation cover are noted by a change in brightness value (intensity) from one date to the next and the spectral direction of that change (change in color) as is illustrated in Fig. 4.9. For example, if an area was forested in the early image and was soil in the more recent image, there would be a change in intensity since soil tends to be bright in most spectral bands and forest tends to be darker and there would also be a notable directional component since the "color" of a forest is quite different from the "color" of bare soil.

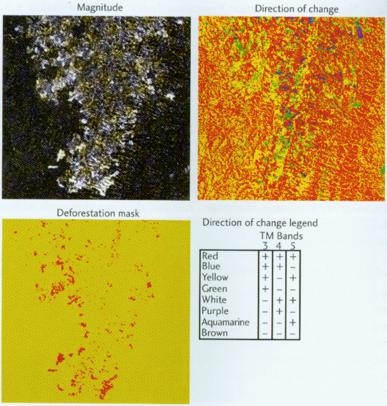
Spectral change vector analysis provides two output images: intensity of the change vector and direction of the change vector. The intensity value is similar to what is calculated using image math although spectral change vector analysis typically uses multispectral imagery whereas image math is usually limited to single-band comparisons. This approach shares some of the drawbacks with image math but they are less severe and using the direction information in combination with the intensity information allows you to classify land cover change into different types.

4.2.4.6 *Hybrid approach*

You can also us a hybrid approach similar to that described in the land cover classification section above to leverage the advantages of both automated and manual methods.

4.2.5 Dealing with different data sources

Although it is best to use data from the same sensor, one of the practical realities of change detection is that you are often forced to use different types of imagery for the different time periods that are of interest. For example, if you want to calculate changes in land cover starting with a period before 1972 you will almost



	3	4	5
Red	+	+	+
Blue	+	+	−
Yellow	+	−	+
Green	+	−	−
White	−	+	+
Purple	−	+	−
Aquamarine	−	−	+
Brown	−	−	−

Fig. 4.9 Spectral change vector analysis can be used to determine the magnitude of change between two dates and the spectral direction of that change. We calculated magnitude and the spectral direction of change using Landsat TM and ETM+ bands 3, 4, and 5 (red, near-infrared, and mid-infrared, for the two Landsat images shown in Fig. 4.3). The magnitude image shows you how much pixel values changed from one date to another, with brighter pixels representing greater change. The direction of change image indicates whether the pixel values for individual bands increased or decreased between the two dates. For example, the blue color shows that for bands 3 and 4 pixel values increased (+) from the earlier date to the more recent date and band 5 decreased (−) in value. In the deforestation mask the red color illustrates all pixels that have a magnitude greater than 35 and increases in pixel values for bands 3 and 5 and a decrease for band 4. This corresponds roughly with areas that have been deforested. In this example only three bands were used to more easily explain the process; however, more bands can be used. Credit: Ned Horning, American Museum of Natural History's Center for Biodiversity and Conservation.

certainly be limited to using aerial or satellite-based photography as data layers because digital imaging land remote sensing satellites did not exist before 1972. Another common example of using different types of data is comparing Landsat MSS, TM, and ETM+. Historic data from Landsat MSS has a lower spatial resolution and a more limited band set than TM and ETM+.

However, how do you deal with change detection when using different data types? One solution, and probably the most common when aerial photos are compared to satellite imagery, is to use the visual on-screen digitizing methods described above. This approach is easier if the two image types are both in digital format (the aerial photos can be scanned) and georeferenced so that they can be displayed in a coordinated manner on a computer screen.

If both data sets are multispectral in nature you can resample one of the data sets so that the pixel sizes for the two data sets are equal. When this is done the coarser resolution data set is usually resampled to equal the resolution of the other data set. This, of course, does not effectively increase the information content of the coarser resolution image but it does provide a data set that can be processed using the automated methods described above without compromising the detail of the higher-resolution image. Some GIS and remote sensing software packages allow you to combine imagery with different resolutions and in that case resampling would not be necessary.

4.2.6 Data normalization

There is a lot of debate in remote sensing circles about the practical value of normalizing images before conducting change detection classification (Song *et al.* 2001). Data normalization is primarily aimed at making the two images used as input for a land cover change analysis similar with respect to radiometric qualities so that the same land cover type on the two images has the same brightness value (digital number). In other words, it is an attempt to simulate the illumination and atmospheric conditions present when one of the images was acquired. The idea is that if the images are normalized, then it is much easier to note changes from one cover type to another since any change in brightness value between the two images will indicate a change in land cover. Even though this logic is quite sound, in practice it can be difficult to accomplish. There are two primary reasons for this. The first is that it is difficult to accurately create two normalized images. This is largely because the variations caused by illumination and atmospheric effects are rarely homogeneous across an image and simple and reliable methods to normalize imagery are still being perfected (Hashim *et al.* 2004). The second issue is that there is often a change in the state of the land cover between the two dates due to senescence, green-up, disease, or simply different growing conditions (growing degree days, water availability . . .) so the assumption that similar land cover types will look the same on both images is not always valid.

Although one can argue that any improvement gained from data normalization will improve classification accuracy, from our experience investing a significant effort into normalizing images using sophisticated algorithms does not always decrease the time spent on conducting the change detection or increase the accuracy of the output. Access to easy-to-use but complex data normalization algorithms is improving but in the past these capabilities have generally been restricted to expensive image-processing software programs. These algorithms may produce more accurate surface reflectance measurement but they often do not do as well normalizing the difference between the two images, which is important when doing change detection analysis (Song *et al.* 2001).

Two simple methods that you can use to normalize multi-date images are dark object subtraction and histogram matching. The dark object subtraction method works on the assumption that the darkest object in an image will have a very low (undetectable) surface reflectance in each of the image bands. To apply this approach you need to determine the lowest pixel value from the histogram of an image band and then subtract that value from all the pixels in that band. This process is repeated for all image bands. With histogram matching one of the images is used as a reference and the goal is to modify the histograms of the other images acquired on different dates so that they match as closely as possible. The closer histograms from the reference and other images are, the more similar the images will appear when visually inspected. The histogram matching process is available in most remote sensing software packages but it should only be used when the different images were acquired from the same sensor. Both of these normalization methods assume the atmosphere is uniform throughout the image.

4.2.7 Validating change detection results

Validating the results of a land cover change map can be difficult because one needs to determine what the land cover was for the time periods that are being compared. Typically when you assess the accuracy of a land cover map you can collect ground reference data on existing land cover but how do you go back in time to verify past land cover? The best answer to this is to use whatever information is available. In some cases you might be able to find aerial photos that can provide sufficient detail for the time period of interest. A possibility, although rarely practical, is to use interviews from people familiar with the landscape.

If you are putting in place a project to systematically monitor land cover change over time, it is advisable to set up permanent plots or use some other method for systematically sampling the same area so that the areas or plots can be checked every time a new layer is added to the land cover change series of maps. A simple way you can accomplish this is to periodically take photographs of an area from the same observation point (Section 13.1.3). This way you effectively keep a running tally of the change situation on the ground for specific areas.

4.2.8 Planning a land cover change project

Many of the issues that you address in a land cover mapping project (Section 4.1) must be addressed when mapping land cover change. For example, the change

Table 4.2 Biological and physical characteristics that affect the ease and resulting accuracy of mapping changes in forest cover over time.

Characteristic	Relatively easy	More difficult
Terrain	Flat terrain	High hills or mountains
Phenology	Predictable and homogeneous	Heterogeneous changes
Cloud cover	Rare morning clouds	Near continuous cloud coverage
Tree density	Closed canopy	Low percent crown closure
Fragmentation	Large contiguous coverage	Small patches of forest/non-forest

classes have to be thoughtfully selected so that they meet the objectives of the project and can be accurately delineated using the methods selected. The same goes for the selection of image dates that will be used for determining land cover change. The images have to provide sufficient spatial and spectral information to allow the detection of significant changes in the landscape. As for the selection of methods, it is important that the people doing the classification have sufficient experience in those methods so they can be performed reliably and consistently.

There are a number of additional issues that you must consider when creating a change detection map. The biological and physical characteristics of the area greatly impact the ease and accuracy for which land cover change can be monitored. Many of these characteristics are summarized in Table 4.2.

In a perfect world, all of the sensor and environmental conditions would be relatively equal in both the early and late date images but in practice many or even all of these are beyond your control and you just have to do the best you can with the available imagery.

Here is a list of some variables worth considering when selecting imagery for a land cover change project.

4.2.8.1 Sensor characteristics

Ideally one would like to use imagery from the same sensor to keep the sensor characteristics as consistent as possible. The more similar the characteristics of the sensors (Section 2.1.1), the more likely you are to have similar features on the ground appear similar in the two image dates.

Even using imagery from the same sensor is no guarantee that the sensor characteristics will be equal since sensors degrade over time thereby changing the radiometric qualities of the sensor and in some cases causing a partial loss of data. The degradation of a sensor can often be compensated by applying published radiometric correction factors or simply by ordering radiometrically corrected imagery. As an example of the major changes that can occur, the Landsat ETM+ Scan Line Corrector (SLC) failed on May 31, 2003, and since that time, there are lost scan lines on the edges of each scene, with a 22 km swath in the middle that has full data (Markham *et al.* 2004).

4.2.8.2 *Solar illumination*

Images acquired under similar solar illumination configurations help ensure that ground features will appear similar on both early and late date imagery. If solar illumination angles are similar then shadowed areas as well as brightly illuminated areas will be similar in appearance for both dates. To accomplish this it is necessary for the imagery to be acquired during the same time of the year and the same time of the day. Some of these effects can be reduced using a DEM to normalize the effect of differencing illumination angles but this approach is not perfect (Riaño *et al.* 2003).

4.2.8.3 *Atmospheric conditions*

Ensuring similar atmospheric conditions between two dates of imagery is much harder to control than many of the other variables as it tends to change on an hourly or daily basis and is not always homogeneous across an image. Acquiring imagery at approximately the same time of the year can increase the chances of meeting this goal but it is certainly no guarantee. As with the solar illumination variable, atmospheric effects can be reduced using atmospheric correction algorithms but this too is an imperfect solution. See Section 4.2.6 on data normalization for more insight into this problem.

4.2.8.4 *Soil moisture*

Differences in soil moisture between two images acquired on different dates can affect change detection analysis in direct and indirect ways. It can directly affect interpretation of features when soil makes up a significant portion of the signal. This is especially noticeable when image bands that are sensitive to water, such as Landsat TM band 5, are used in the analysis.

Soil moisture can indirectly affect plant productivity (primary productivity is higher when plants have abundant water) thereby altering the reflectance characteristics of similar vegetation so it may appear as if the vegetation composition has changed (Mas 1999).

4.2.8.5 *Acquisition date and frequency*

The acquisition date of imagery is important for a number of reasons. In addition to those stated above, it is best to select a time of the year when you can most accurately differentiate the features in which you are most interested. This way it will be easier to detect changes in that cover type. For example, if you want to monitor changes in deciduous land cover, you would want to avoid using imagery acquired during green-up or senescence since the vegetation you are interested in is changing rapidly and it is nearly impossible to acquire an image from another time period with vegetation in the same state of green-up or senescence.

Another issue related to the acquisition date is the frequency of acquisition. If you are interested in monitoring changes over a relatively short period of time, you need to make sure that sufficient imagery is available for the focal time periods. The acquisition schedules for some sensors are predictable but even if you know when a satellite will acquire an image you are not able to predict if that image will be of sufficient quality (due to an array of environmental contaminants such as clouds or haze) to effectively perceive change in land cover. If the frequency for monitoring is on the order of several years then this is less of a concern.

Typically, you would try to acquire images from the same time of the year to reduce differences due to solar configuration and vegetation phenology.

4.2.8.6 Water levels

When working in areas with water, it is important to be aware of changes due to differences in water levels. If the change is permanent, it is certainly important to record it accordingly, but if it is periodic such as with tides and floods, then knowledge of these events and their timing should be considered when selecting imagery and during the interpretation phase. For example, the level of standing water in wetlands can vary greatly over time (Section 7.2). Viewing images acquired at times when water levels were not the same can present a very different picture of the wetland.

4.3 Vegetation characteristics

In terrestrial biomes, ecologists and conservation biologists need information about vegetation cover beyond what can be inferred from land cover maps. This section discusses ecologically relevant measures of vegetation that you can make using passive and active remote sensing sensors. Coverage of this topic includes how the measurements are made, how they compare with ground-based measurements, and how they can be used to understand the status or condition of the vegetation, the foundation of terrestrial ecosystems.

Some of the methods discussed in this chapter have been applied to global data sets to provide input to a number of models that require information about primary productivity. As remote sensing technology and algorithms improve, the ability to accurately monitor a variety of vegetation characteristics will increase.

There are a number of satellite image-based products that are being used to monitor vegetation over large areas around the world (Morton *et al.* 2005). For example, data collected from the MODIS sensor are used to create a number of products related to vegetation. These include (with the standard product reference)

- Vegetation indices (Section 4.3.1) (MOD13)
- Land cover (MOD12)
- Vegetation cover conversion (MOD44A)

- Vegetation continuous fields (VCF)/percent woody vegetation, herbaceous cover, and bare ground (MOD44B)
- Phenology (MOD12Q2)
- Leaf area index (LAI) (MOD15A2)
- Net primary productivity (MOD17A3)
- Fraction of absorbed photosynthetically active radiation (MOD15A2)

Measurements of these characteristics are based on the fact that reflectance, transmittance, and scattering of energy in a canopy are greatly affected by the structure and composition of the vegetation and how the vegetation components (leaves, branches, and trunk) interact with the spectrum of energy being used by a particular remote sensing instrument.

One quality that differentiates most of the vegetation characteristic data sets listed above from classified maps is that they are continuous representations of the attribute being mapped instead of discrete classes as is the case with land cover mapping.

4.3.1 Using vegetation indices

You can calculate vegetation indices with algorithms that rely on the fundamental principle that chlorophyll in green unstressed vegetation strongly absorbs red and blue wavelengths of light and strongly reflects infrared wavelengths (Glenn *et al.* 2008). This can be observed by looking at image bands recording red and infrared light (Fig. 4.10) or at a reflectance curve for vegetation (Fig. 3.15). Areas with a high density of green vegetation have a high vegetation index value and those with little or no green vegetation have a low value.

Vegetation indices have been used extensively for global studies to monitor changes in vegetation and have been effective in mapping droughts, desertification, phenology, and deforestation around the world. There are several reasons for this:

- There is a positive and strong relationship between vegetation indices and primary productivity (Tucker and Sellers 1986).
- The algorithms are, in general, simple and as a result they only require moderate computer power.
- Suitable imagery (at 1–4 km spatial resolution) has been acquired daily since 1978 for regions on Earth except the poles.

Most global products are available as multiday composites to reduce the effects of cloud cover and poor-quality data. Composites are created using a variety of periods such as 8 days, 10 days, 16 days, and monthly. Compositing routines use logic so that the "best" quality value for the composite period is selected. Historically, the "best" value simply equaled the highest index value during the compositing period. Now, more sophisticated logic incorporates several factors such as the number of "good" index values during the compositing period (Chen *et al.* 2003).

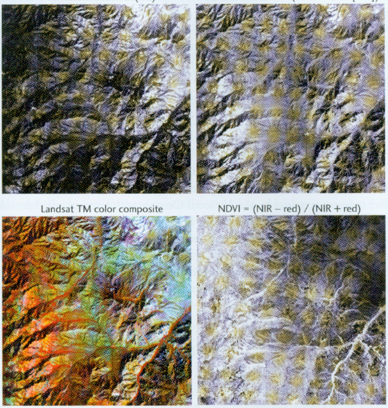


Fig. 4.10 In an NDVI image, vegetation has a high value since chlorophyll in green vegetation heavily absorbs red wavelengths and reflects most of the near-infrared wavelengths of light. In this Landsat TM image of an area in southeastern Arizona you can see the heavily vegetated areas along streams and in the mountains toward the left portion of the image produce higher NDVI values then the sparsely vegetated areas toward the upper right corner of the image (Landsat ETM+ image; path 35; row 38; September 12, 2000). Credit: Ned Horning, American Museum of Natural History's Center for Biodiversity and Conservation.

In addition to primary productivity, vegetation indices have also been used to estimate parameters such as LAI. However, one of the limitations of using vegetation indices for these measures is that they are not very sensitive in high biomass and LAI environments since the indices saturate easily (Huete *et al.* 2002). To get around this problem you can use other algorithms. These improved algorithms are used to create a number of data products related to productivity that are based on the MODIS instruments (Appendix 4) on

NASA's Terra and Aqua satellites. MODIS provides near-daily global coverage at resolutions ranging from 250 m to 1 km.

We will discuss two common vegetation index algorithms: the NDVI and the Enhanced Vegetation Index (EVI). There are several other vegetation indices that have been described in the literature (Huete *et al.* 1997), such as the Simple Vegetation Index (SVI), Soil Adjusted Vegetation Index (SAVI), and the Modified SAVI (MSAVI), but the two indices presented below illustrate the basic principles of how vegetation indices work.

4.3.1.1 NDVI

The NDVI is the most common vegetation index and it has been in use since the 1970s (Rouse *et al.* 1973). It was applied to a global data set of coarse-resolution satellite imagery acquired by the National Oceanic and Atmospheric Administration (NOAA)-operated Advanced Very High Resolution Radiometer (AVHRR) sensors. The first AVHRR sensor was launched in 1978 and successive AVHRR instruments continue to provide nearly global coverage. Creating NDVI layers from this global data set proved to be an efficient way to get a good overall picture of primary productivity in terrestrial landscapes at a global scale (Tucker and Sellers 1986). The formula for the NDVI is:

$$\mathrm{NDVI} = \frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + \mathrm{Red})} \tag{4.1}$$

where NIR = the near-infrared channel image value and Red is the red channel image value (Fig. 4.10). This generates a number between +1 and −1. Areas with a lot of unstressed green vegetation will have a value well above 0 and areas with no vegetation will be close to 0 and in some cases will have negative values. As a plant is stressed its productivity decreases so stressed vegetation will have NDVI values lower than unstressed vegetation (Kogan 2001).

4.3.1.2 EVI

The EVI was developed to improve upon the NDVI algorithm (Huete *et al.* 2002) and is gaining in popularity because it is offered as a MODIS data product.

The MODIS algorithm for EVI is:

$$\mathrm{EVI} = G^{*}\left[\frac{(\mathrm{NIR} - \mathrm{Red})}{(\mathrm{NIR} + C_1{*}\mathrm{Red} - C_2{*}\mathrm{Blue} + L)}\right], \tag{4.2}$$

where NIR = the near-infrared channel image value, Red is the red channel image value, Blue is the blue channel image value, and the four coefficients (they are constants when used with MODIS) are:

- Gain factor, $G = 2.5$
- Canopy background adjustment, $L = 1$

- Atmospheric aerosol resistance, $C_1 = 6$
- Atmospheric aerosol resistance, $C_2 = 7.5$

This is similar to the algorithm for NDVI but it adds corrections to reduce the effects of radiometric contaminants from the atmosphere and within a canopy. The canopy background adjustment coefficient L compensates for the different ways in which near infrared and red light behave (scattered and absorbed) inside and below a canopy. Soil moisture, surface litter, snow, and the type of soil all influence NDVI. The EVI is also more sensitive to variations in dense vegetation where NDVI tends to get saturated. The atmospheric aerosol resistance coefficients C_1 and C_2 reduce atmospheric effects in the red channel using data from the blue channel.

The EVI is more sensitive to canopy structure whereas NDVI is more sensitive to chlorophyll content so these two indices tend to complement each other. In fact, the MODIS Vegetation Indices product (MOD13) contains both NDVI and EVI products. It should also be noted that the imagery used to create the MODIS vegetation indices products are preprocessed to reduce the effects of viewing angle and solar illumination angles. If you need finer resolution than what is available from the MODIS products, you can always create your own vegetation indices using imagery with a finer spatial resolution and image-processing software (Appendix 2).

4.3.2 Principle components analysis (PCA)

Another technique that uses multispectral imagery to create a data set indicating the amount and status of green vegetation is PCA. Used throughout multivariate statistics, principal components analysis is a vector space transformation for multivariate data that transforms a number of correlated variables into a smaller number of uncorrelated variables called principal components. In remote sensing, it transforms a set of multiple bands into a new smaller set of principal components that describe the same image. Each successive component image will contain a lower percentage of the total variance. In other words, the first principle component image will contain most (often more than 85 percent) of the total variance from the original multispectral image and the second image will contain much less and the third even less variance.

A standardized PCA approach called the *Tasseled Cap transformation* has been developed for data sets acquired by different sensors. Using the Tasseled Cap transformation coefficients, it is possible to compare component images created using imagery from different times of the year or from different areas. The second principle component of a Tasseled Cap transform is called "greenness" and it is often compared with NDVI as an index of vegetation productivity. PCA can also be used to detect changes in land cover over time when applied to a time series vegetation index data set. When using a NDVI time series data set, the second principle component is considered the change component although the higher order components also are related to changes in land cover over time.

When interpreting the results of PCA you will need to identify the type of land cover change (i.e., seasonal, deforestation, and reforestation) that is most strongly associated with each of the component images.

We will also mention uses of PCA in other chapters in the book, and there is a detailed example using PCA with other classifications methods in Section 7.1. It can be used as a classification approach in its own right, and also for data reduction when there are a large number of bands.

4.3.3 Other MODIS vegetation data products

Two MODIS vegetation data products, in addition to the Vegetation Indices product (MOD13), that can help you understand vegetation cover and dynamics are the Global Land Cover Dynamics (MOD12Q2) and Vegetation Continuous Fields (MOD44B).

If you are interested in studying phenology, the MODIS Global Land Cover Dynamics data set (MOD12Q2) may be useful (Zhang *et al.* 2003c). The MOD12Q2 product includes a number of data sets with information about phenological cycles over a 12-month period including: onset of greenness increase, onset of greenness maximum, onset of greenness decrease, and onset of greenness minimum. These data are generated using a phenology detection algorithm that uses the MODIS EVI data set, described above, to track the green-up and senescence of vegetation around the globe. The algorithm uses data from other MODIS data sets to account for cloud cover, snow, and surface temperatures that are too low to support vegetation growth. One issue to keep in mind when using the MOD12Q2 product is that the EVI data used in the algorithm are available only every 16 days so the temporal scale is quite coarse. Consequently, the timing of greenness and senescence provided by the MOD12Q2 data set are only approximate.

The MODIS VCF data set (MOD44B) provides information about the density of vegetation (Hansen *et al.* 2003). Each pixel represents the percent cover within that pixel. For example, for percent tree cover each pixel would indicate the percent of that pixel that is covered by trees. A pixel value of 70 means that 70 percent of the pixel is covered by trees. This provides the ability to detect subtle differences in vegetation cover that would not be detectible in a typical land cover map. However, using the continuous fields approach requires that a separate layer be generated for each land cover type of interest. The MOD44B data set provides the following layers: tree cover, herbaceous cover, and bare cover at a spatial resolution of 500 m.

4.3.4 Using active sensors for vegetation mapping

Passive optical sensors that use the sun as the energy source are effective at providing information about the surface of a canopy but provide little information about what is under the canopy. To get subcanopy data we need to look at the different active sensors such as radar and lidar systems that emit their own energy source. These active sensors consist of a detector and signal generator whereas passive systems require only a detector. Radar is an acronym for radio detection and ranging. Radar systems operate in the microwave portion of the electromagnetic spectrum (Appendix 1) and because of this the signal is largely unaffected by clouds and rain so it can be considered an all-weather system. Lidar is an acronym for light detection and ranging and these systems operate in the visible and near-infrared portions of the electromagnetic spectrum.

Active sensors emit a signal and then measure its return properties. Since the signal is sent in regular pulses, the time it takes for the signal to return can be measured. It is this ability to measure different properties of the returned signal that allows active remote sensing systems to measure vegetation structure.

4.3.4.1 *Radar systems*

Radar is a rapidly evolving technology for measuring vegetation properties such as biomass, LAI, forest structure, and forest inventory information such as tree height and timber volume. Radar systems interact with materials differently from optical systems. Passive sensor systems record energy reflected from the surface of objects, such as trees, whereas radar energy can penetrate the canopy surface and interact with the vegetation elements such as leaves, branches, and trunks. These elements are large compared to the shorter radar bands (Appendix 1) such as the K-band and X-band but are small when compared to the longer L and P radar bands. The shorter wavelengths (i.e., K-band and X-band) are scattered more within a canopy whereas the longer wavelengths (i.e., L-band and P-band) are able to penetrate the canopy and in some cases even penetrate the soil before being scattered back to the radar's receiver.

The way in which a radar signal interacts with different objects, and therefore the intensity of the *backscatter* (returned signal), depends on the object's size, shape, surface roughness, angle of the incident microwave energy, and dielectric constant. An object's dielectric constant is a measure of the material's electrical properties with respect to the degree to which it absorbs, reflects, and transmits the incoming energy. Materials such as metal, water, and healthy vegetation have relatively high dielectric constants (meaning they reflect most the energy that strikes them) compared to soil, dead vegetation, or vegetation with very low water content (which generally absorb energy that strikes them). In other words, features such as a healthy forest will produce a brighter image than soil or a stressed forest.

The components that make up a vegetation canopy scatter and absorb radar energy hitting the canopy. The radar system measures the strength of the backscatter (the portion of the emitted energy that is received by the radar antenna) and the time delay between when the energy was emitted and when it was received. These two types of information are used to measure vegetation structure.

Another useful property of radar systems is the polarity of the signal. When a radar emits a signal it leaves the transmitting antenna with either horizontal (H) or vertical (V) polarization (the direction of vibration of waves of electromagnetic radiation). After the signal interacts with features on the Earth's surface the antenna in either the horizontal or vertical direction receives it. The polarization of a particular data set can be HH, VV, HV, or VH where the first letter represents the polarization for the transmitted signal (horizontal or vertical) and the second letter is the polarization of the received signal. Using these different polarization configurations allows analysts to differentiate features based on how a feature modifies the polarization of the microwave signal. Creating a color composite using the different polarization combinations, it is possible to distinguish visually among different vegetation types (Fig. 4.11). Vegetation structure elements such as size, shape, and orientation have a definite albeit complex effect on polarization. The behavior of the polarization effects is also dependent on wavelength so polarization will behave differently depending on the wavelength of the radar signal.

Studies have shown that there is a relationship between the intensity of radar backscatter and forest biomass (Imhoff 1995). Longer wavelengths, such as the P-band, tend to be better predictors of biomass than the shorter wavelengths since the shorter wavelengths do not penetrate into the canopy as well as the longer wavelengths. Researchers are also seeking to better understand how biomass affects polarization. One drawback of using radar to estimate biomass is that biomass estimates tend to saturate at moderate biomass values so radar is not sensitive to variations within areas with high biomass (Imhoff 1995). Another problem is that surface wetness modifies the radar return adding more uncertainty to biomass estimates. Using radar to estimate biomass is also a labor-intensive effort since field surveys must be carried out to physically measure the biomass at several sites and then correlate this information with the data in the radar image. As research continues biomass estimation methods using radar might become an effective operational tool for measuring and monitoring biomass over large areas.

Forest characteristics such as height, density, and volume can also be measured using radar. As with estimating biomass, radar data using different wavelengths and polarization configurations are correlated with field data to see which configurations are best suited for measuring a particular characteristic.

Another technique for characterizing forest structure is *radar interferometry* (Section 5.1.3). The Shuttle Radar Topography Mission (SRTM) used this technique to create a near-global DEM using a radar system flown on the space shuttle. Interferometry use two radar images of the same area but which were acquired from slightly different locations. For the SRTM mission, one of the radar systems was mounted in the Space Shuttle cargo bay and the other was mounted on the end of a 60 m boom (Fig. 4.12). Two images can also be acquired using multiple passes by a satellite-based radar system as long as the exact distance between the two image acquisitions is known. If the distance between the two radar acquisitions is known, you can use sophisticated analysis techniques to calculate the height of objects on the ground. This method has been proven to produce high-quality DEMs (Gelautz *et al.* 2004) and research is

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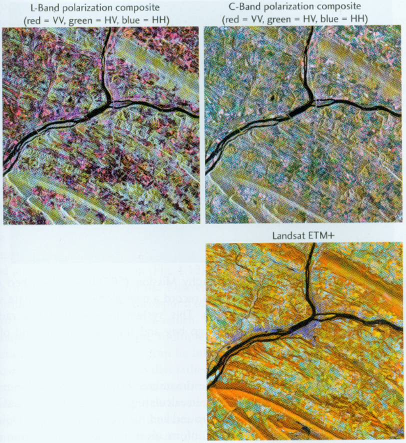

Fig. 4.11 Color composites can be created from radar data by combining images acquired with different polarization configurations. The top two images of an area around Sunbury, Pennsylvania, USA, show how radar data can be displayed as color images. The top two images are SIR-C/X-SAR data for L-band (5.8 cm wavelength) and C-band (23.5 cm wavelength). For each image the color composite was created by combining the following polarization combinations: VV, HV, and HH where the first letter is the transmitted polarization (either vertical or horizontal) and the second letter is the received polarization. Therefore, "HV" means that the signal was transmitted with a horizontal polarization and received with a vertical polarization. Combing different polarizations in a color composite helps you identify features on the ground (SIR-C/X-SAR data from October 6, 1994). The third image provides a view of the same area using an optical sensor (Landsat ETM+; bands 4, 5, 3 displayed; path 15; row 32; October 5, 2001). Credit: Ned Horning, American Museum of Natural History's Center for Biodiversity and Conservation.

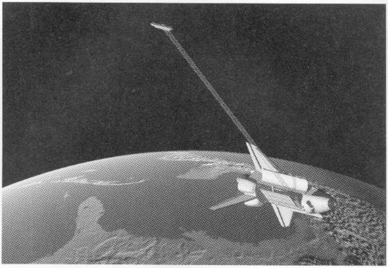

Fig. 4.12 The Shuttle Radar Topography Mission (SRTM) was launched on February 11, 2000 with the mission to record a near global elevation data set using an interferometric radar system. This system incorporated two radar antennas; one in the space shuttle cargo bay and the other on the end of a 60 m mast. Credit: NASA/JPL-Caltech.

ongoing to use radar interferometry to estimate tree heights and forest biomass (Kellndorfer *et al.* 2004). The main issue in calculating tree height is the necessity to measure the difference between the ground and the top of the canopy. Doing so requires the extraction of additional information. For more information on SRTM elevation data see Section 5.1.3.

With the increase in availability of satellite-based radar data, these data are increasingly being used to produce land cover maps and provide other information about habitat, especially as a complement to optical data or in areas with persistent cloud cover. While radar methods are still quite experimental with regard to the study of vegetation structure, research in this area is quite active (Kellndorfer *et al.* 2004, Treuhaft *et al.* 2004).

Radar data provide useful information. However, the techniques and software required to process radar data are still somewhat complex and, for the most part, beyond the capabilities of most conservation practitioners. In some cases, purchasing products derived from radar data such as land cover maps or collaborating with others who have experience working with radar data may be more feasible than buying the raw data and processing it yourself.

4.3.4.2 Lidar systems

Although lidar is probably best known for its use in creating digital elevation data, lidar systems show a lot of promise for the direct measurement of vegetation

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structural characteristics. Unlike radar and passive optical systems, lidar can directly measure vegetation structure and provide a vertical dimension largely missing in passive optical and radar data.

Lidar measures the distance between the sensor and a target by timing when the signal, a pulse of light, is transmitted and when received. Most of the laser systems used to measure vegetation structure use lasers that emit infrared light since vegetation is highly reflective in the infrared wavelengths, although certain bathymetric lidar systems utilize the water-penetration capabilities of green wavelengths.

Lidar systems use a pulsing laser and sensor that are flown in an airplane or onboard a satellite. In the simplest single pulse system, a laser pulses in rapid succession so the sensor collects data along a transect. The spacing of the pulses on the ground depends on the speed of the aircraft and the rate of the pulses being emitted. After a pulse hits a feature, the light is reflected back to the sensor. Only a portion of the light is reflected off of the top of the canopy and some of it continues down and interacts with other features within the canopy and other layers of vegetation (Fig. 4.13). The receiver in a lidar system measures the intensity of these returns. Discrete lidar systems only measure specific portions of this signal that correspond to peaks of returned energy. Some discrete systems only measure the first return, which is assumed to be the top of the canopy, while others measure multiple returns so that information about the vertical dimension of a forest can be inferred. More sophisticated lidar systems record the entire waveform so that rather than simply measuring the peaks in the returned signal the entire waveform is recorded (*waveform lidar*; Fig. 4.13).

Discrete lidar systems tend to have much higher spatial resolution because of their small footprint (size of the laser spot on the ground) and the rapid rate of emitting laser pulses (as high as 30,000 points per second). The primary advantage of waveform lidar is that it records more data from which to infer vegetation structure.

Lidar systems do not create images such as those created in typical optical remote sensing instruments. Although mapping lidar systems exist, the systems often used to measure forest structure provide points along a transect. A scanning lidar is a more recently developed system that provides enough points to enable an image to be constructed and is quite often used in marine, coastal, and wetland applications (Chapters 6 and 7).

The simplest measurement from a lidar system is the height of a canopy and the area covered by a canopy. With a well-designed sampling scheme and field plots to relate tree height with biomass, you can estimate biomass for very large areas, along with other forest stand characteristics. It is also possible to predict the percentage of light that is transmitted through different levels in the canopy. This is important when trying to understand how much light is available to organisms as you move from the top of a forest canopy to the forest floor.

By recording the intensity of the returned lidar signal you can derive a number of canopy structure indices. One of these indices is canopy volume, which is an

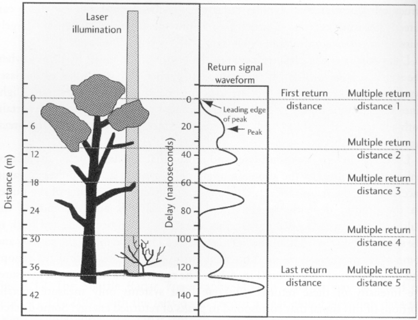

Fig. 4.13 When a laser pulse comes into contact with a forest, some of the energy is reflected from the top of the canopy but the rest enters the canopy and is reflected off of different elements of the tree, undergrowth, and eventually the ground. Depending on the type of laser being used, you can record varying amounts of data to understand the structure of the forest vegetation. The simplest lidar systems record only the first return distance. Other discrete-return systems record first and last and some record up to five discrete returns. The most sophisticated lidar systems can record full waveform data. Figure redrawn from Lefsky *et al.* (2002: 20), ©American Institute of Biological Sciences.

index that describes the surfaces of leaves and branches in three dimensions (Lefsky *et al.* 2002). Additional canopy indices will almost certainly be developed as lidar research continues. Canopy indices are potentially very important with respect to mapping habitats.

As of 2003, the only satellite-based lidar system used for vegetation studies is the Geoscience Laser Altimeter System (GLAS) onboard the Ice, Cloud, and land Elevation satellite (ICESAT). GLAS was developed primarily for measuring elevation and to determine ice sheet mass balance. There are a number of commercial and experimental airborne lidar systems acquiring data around the world. Scientists are only beginning to grasp the full potential of lidars for measuring vegetation structure and much research is going on in this arena (Behera and Roy 2002; Lefsky *et al.* 2002; Goodwin *et al.* 2006). Commercial airborne lidar systems exist. You can purchase aerial overflights of many locations with lidar and multispectral sensors. If you are interested in exploring the use of this technology, it may be well worth your time to contact some of these companies and ask them about the characteristics and capabilities of their systems. NASA is designing a satellite with a "vegetation-appropriate" lidar onboard called DESDYNI, planned for launch in 2014.

4.4 Summary

Satellite and airborne remote sensing provides a range of data and methods that can be used to study land cover, land use, and vegetation characteristics. You can successfully conduct simple analyses such as visual inspection of imagery. More complex techniques such as the creation of vegetation indices and land cover classification can be carried out with minimal training and experience. More complex analysis methods, especially those involving radar and lidar data, require more in-depth training. Fortunately, there are a number of high-level products derived from remotely sensed data that are available, with some available for free or at low cost. As these remote sensing systems improve, you can expect to see products that can be used to more precisely and accurately map features around the globe.