Remote Sensing in Forest Health Protection

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REMOTE SENSING IN
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1. INTRODUCTION

Protecting the health of forest ecosystems is a vital resource management function. An effective forest health protection program requires many kinds of information: information is needed about the condition of forests with respect to growth rates, levels of stocking, fuels, diversity and age. Information is also needed on the status of insects, diseases, and other damaging agents that can adversely affect the ability of forests to produce the goods and services for which they are managed and on the ecological, social, and economic consequences of those agents.

This information is used to formulate alternative management actions that might be taken for improving forest health and to project the benefits and consequences of these actions. When an appropriate course of action is determined, additional information is needed to evaluate the effects, both positive and negative, of that action. Consequently, monitoring the health of forests and the status of insects, diseases, and other agents that affect forest health is a key part of forest health protection.

Data collected to support forest health protection must address a number of questions including:

- **What is the condition of the forest?** Are damaging agents present at levels that could adversely affect management objectives? What are these agents, and how are they affecting forest health?

- **Where is the problem?** Occurrence of a forest health concern must be described in a spatial context, with regard to political units affected (states, counties, townships), land ownership, and landscape features such as vegetation types and topography (elevation, slope, and aspect).

- **How severe is the problem?** Data is needed on the area involved and resources affected, and whether areas exist where the problem is more severe than others.

- **Why is the problem occurring?** The presence of an insect or disease causing widespread damage is often a symptom of a deeper forest health problem. Therefore, it is necessary to examine site and stand conditions, past management practices, climatic anomalies, and other conditions that may favor the spread of damaging agents.

- **What is the probability of a problem occurring?** Stand conditions such as stocking levels, age, species diversity, or soil conditions can result in poor health, and predispose forests to damage by a variety of pests. Tree and stand hazard rating systems have been developed for a number of forest ecosystems and are helpful for defining opportunities where treatments to prevent damage can be implemented.
1.1. REMOTE SENSING DEFINED

Remote sensing is defined as the **collection and interpretation of data based on the measurement of electromagnetic energy reflected or emitted from those objects** (RSAC n.d.). Another aspect of remote sensing is that the data about objects is gathered from a distance, without touching the objects. The human eye, coupled with the human brain is a type of remote sensing system. Every time we look at something from a distance and try to interpret what we see, we are sensing remotely. Some examples of everyday activities in forest health protection that involve remote sensing include the completion of aerial surveys to detect and map the severity of forest damage caused by insects and diseases, and the interpretation of an aerial photograph to map and classify forest damage.

While many remote sensing approaches still involve the use of the human eye as the principal tool for gathering information, modern technology has made many more tools available to collect data for assessing a wide range of natural resource issues and concerns. These include an array of camera systems, scanners, and temperature sensing-devices. They can be ground-based, airborne, or placed in Earth-orbiting satellites. Advances in computer technology have resulted in systems capable of analyzing, storing, and displaying huge volumes of data acquired from these sensors. Moreover, navigation systems are available that are capable of pinpointing the location of features on the Earth’s surface with a high degree of precision and geographic information systems (GIS) that provide for the storage and display of spatial information derived from remote sensing systems.

1.2. WHY IS REMOTE SENSING OF INTEREST IN FOREST HEALTH PROTECTION?

Forest damage caused by insects, diseases, and other agents is often highly visible from long distances. Some types of forest damage, such as crown discoloration and dieback, are actually much more visible when seen from the vantage point of low-flying aircraft or an aerial photograph than when viewed in a dense forest. Consequently, much forest damage lends itself to assessment and measurement by remote sensing. Not only is remote sensing a proven, effective tool for data acquisition; it can produce needed data for large areas of often remote, inaccessible forest lands quickly and at a much lower cost than ground surveys.

Many remote-sensing tools are available to support forest health information needs, and forest health specialists have been making extensive use of these tools for many years. Aerial sketchmapping, for example, has been an integral part of forest health protection programs in both Canada and the United States since the end of World War II. Color and color infrared (CIR) aerial photos have also been used for a wide range of applications. More recently, technologies such as airborne videography, digital photography, and Earth-orbiting satellite imagery have been evaluated for their ability to provide needed information.
1.3. OBJECTIVES AND SCOPE OF THIS PUBLICATION

This manual is designed to serve as a comprehensive reference for forest biologists (e.g., entomologists, pathologists, and other specialists engaged in forest health protection) on the use of remote sensing to acquire information about forest health and forest damage. Damaging agents addressed include insects, disease, toxic chemicals, and climatic anomalies. Detection and mapping of introduced invasive plants in forests and rangelands, a field that has attracted increased interest in recent years, is also discussed. The use of remote sensing for mapping and assessment of wildland fires is not covered: this is considered a separate discipline, with a wide range of specialized techniques, and would require a separate treatment to address adequately.

The subsequent chapters provide descriptions of signatures of interest to the forest health specialist that can be seen from a distance; how to classify, enumerate, and assess the accuracy of data acquired from remote sensing; the remote sensing tools presently used in forest health monitoring; and related technologies, such as geographic information systems (GIS) and navigational aids. Also included are examples of both successful applications of remote sensing in forest health protection, as well as examples of applications that were less than successful. While emphasis is placed on forest health applications of remote sensing in the temperate forests of North America (the U.S. and Canada), examples from other forest regions of the world are also presented.

Glossaries at the end of the document list the acronyms and abbreviations used throughout, and the scientific and common names for plants, insects, and pathogens described in the text.
2. SOME BASICS OF REMOTE SENSING

This chapter introduces some of the basic concepts of remote sensing in order to give the reader an understanding of how various remote sensing technologies perform and how their performance characteristics are described. Also included are brief introductions to two closely related technologies: global positioning systems (GPS) and geographic information systems (GIS).

2.1. THE ELECTROMAGNETIC SPECTRUM

We have seen in Chapter 1 that remote sensing is a means of gathering information in various regions of the electromagnetic spectrum (EMS). The sun is the source of most of the energy received by the earth: this energy is known as electromagnetic energy. Electromagnetic energy travels in waves. The wavelength of energy is the distance between wave crests, measured in microns or micrometers (µm). Electromagnetic energy behaves differently depending on its wavelength.

The sun radiates electromagnetic energy from very short wavelengths, such as X-rays, to long wavelengths, such as television and radio waves. The EMS (Figure 2.1) is a continuum of electromagnetic energy. Names are assigned to certain regions of the EMS based on their properties. For example, the region of the EMS between 0.4 and 0.7 µm is known as visible light and represents the wavelengths of electromagnetic energy that the human eye can see. Most photographic films are also sensitive to this portion of the EMS. Beyond the range of visible light is the infrared (IR) region. The shorter IR wavelengths are light that cannot be seen by the human eye while the longer wavelengths (thermal IR) are sensed as heat.

![The Electromagnetic Spectrum](image)

Figure 2.1. The electromagnetic spectrum.
Sensor tools have been developed to gather information in the regions of the EMS beyond what the human eye can see. Some photographic films are sensitive to both visible light and a small portion of the IR region (to about 0.9 µm). Other sensors, known as thermal-IR sensors, are sensitive to longer IR wavelengths, and are useful for detection and mapping of heat sources or differences in temperature between objects.

2.2. COLOR

While light can be defined in terms of wavelength, it is perceived by the eye in terms of color. The portion of the EMS we see as visible light can be described in terms of three primary colors: blue, green, and red. All objects on the Earth’s surface reflect and absorb slightly different proportions of these three primary colors. As light, moisture, or other conditions change, the light reflectance and absorption characteristics of objects will also change. The result is the virtually infinite variety of colors we see with the human eye. To a forest protection specialist, color is an important quality because so many things of interest, such as tree stress, first appear as a subtle change in foliage color.

Color can be expressed in a variety of ways. Most of us use fairly simple describers of color, such as red, red-orange, scarlet, vermillion, and carmine for various reds. These are satisfactory for most purposes, but occasionally, more precise color definitions are required. An example of a more precise color classification system is one developed by the Munsell Color Company (Munsell 1963). This system describes colors in terms of three attributes: hue, value, and chroma.

**Hue** is the term used to describe chromatic color. Five principal colors are recognized: red, yellow, green, blue, and purple. Five intermediate hues, including yellow-red, green-yellow, and blue-purple, are combinations of principal colors. Color hues are further subdivided on a 10-step scale and assigned an abbreviation and a value: YR 5, for example, is a description of a medium orange hue.

**Value** indicates the degree of lightness or darkness of a color on a scale of grays. Value extends from a pure black (value = 0) to a pure white (value = 10).

**Chroma** indicates the strength (saturation) or degree of departure of a particular hue in relation to a neutral gray. This scale ranges from 0 (neutral gray) to 10 (and—in some cases—to 12, 14, or a higher number).

The Munsell Color Company publishes pages of color chips of various hues, values and chromas. These have been used as aids in describing colors of plant tissues, soil types, and of certain objects of interest on aerial photographs.
2.3. **SPECTRAL SIGNATURES**

The interaction of an object and the electromagnetic energy that bombards that object is unique to that object and is based on its physical properties. Objects with similar physical properties have similar spectral responses, while those with different physical properties will have quite different spectral responses. The response of an object to electromagnetic energy is a combination of energy reflection and absorption, and is referred to as the spectral characteristics or **spectral signature** of that object (Figure 2.2). These signatures are used in remote sensing to distinguish and identify objects.

![Figure 2.2. Spectral signature of green vegetation in the visible and near-IR regions of the EMS (redrawn from Murtha et al. 1997).](image)

Healthy vegetation, for example, appears as a green color to our eyes because it absorbs most of the red and blue wavelengths of light it receives from the sun and reflects most of the green light. Different kinds of vegetation reflect different levels of green light; consequently, they appear as different shades, or hues, of green. Conifers, as a rule, reflect less green light than do broadleaf trees; therefore, they appear as a darker green color. Vegetation also reflects a high proportion of the near-infrared (near-IR) radiation it receives from the sun. Furthermore, the differences in response of different kinds of vegetation to near-infrared light are often greater than they are to visible light. Therefore, the availability of a sensor sensitive to the differences in the near-IR region of the EMS can make it easier for us to identify different kinds of vegetation and vegetation condition. Both color and black-and-white IR-sensitive films have been developed for this purpose.
2.4. ANALOG VERSUS DIGITAL DATA

Remote sensing data can be produced in two forms: analog and digital. Analog data is represented as a continuous physical variable. An example of analog data is temperature data recorded by an old-fashioned mercury thermometer: the level of the liquid can be read and interpolated to indicate a specific temperature, but adheres to no inherent unit. Photographs are another example of analog data. Differences in reflectance are recorded on tiny film grains, resulting in an image consisting of continuous tones that blend into one another. Because it adheres to no specific unit, analog data is difficult to store or manipulate electronically. However, images obtained from analog sensor systems, such as photographs or videographic sensors, can be converted into a digital format to facilitate computer storage, analysis, and display.

Digital data, on the other hand, consists of sets of finite units. On digital remote sensing imagery, these units are known as pixels, and represent an area of land on the ground defined by the spatial resolution of the sensor system (see section 2.6.1). Each pixel has a distinct reflectance value. Some camera systems and all of the scanners aboard Earth-orbiting satellites produce data in a digital format. Digital data easily lends itself to storage, analysis, and display by computers.

2.5. PASSIVE AND ACTIVE REMOTE SENSING SYSTEMS

Remote sensing systems can be classified into two types: passive and active. Passive systems are those that simply sense the available energy within the range of the EMS to which they are sensitive. An active sensor system, on the other hand, is one that sends out its own energy source in the direction of the object of interest and records the strength of the signals received back from the object (Lillesand and Kiefer 1979).

An example of an active remote sensing system is a camera equipped with a flash. The flash sends light to the objects being photographed. Some of the transmitted light initiated by the flash is reflected by the object and is recorded on the film. The same camera, used without a flash under natural light conditions is a passive remote sensing system.

Microwave radar is a classic example of an active sensor. Energy is transmitted in short bursts or pulses in the direction of interest. The strength of the returning signal is then measured and recorded by the radar sensor.

The remote sensing systems of current interest in forest health protection (aerial sketchmapping, traditional aerial photography, airborne videography, and digital aerial photography) are all passive.

2.6. RESOLUTION

Remote sensing systems available today have a wide range of capabilities. These can be described in terms of resolution. Resolution is defined as separation into component parts. In the context of remote sensing, resolution refers to the smallest quantity that can be considered a unit of data. The resolution of a remote sensing system, therefore, defines the lowest limit of that system. No more detail can be obtained or resolved beyond the system’s resolution. Remote sensing systems are described in terms of four kinds of resolution: spatial, temporal, spectral, and radiometric (Lachowski et al. 1996, Perryman 1996).
2.6.1. Spatial Resolution

Spatial resolution answers the question: **What is the smallest object that can be seen, or what is the smallest distance between two objects that will allow them to be seen as separate objects?**

Spatial resolution is a measure of sharpness or fineness of spatial detail. It is a measure of the smallest object that can be resolved by the sensor system. For photographic systems, resolution is the ability of the entire photographic system—lens, exposure, and processing—to render a sharply defined image, and is expressed in terms of lines per millimeter recorded by a particular film under specified conditions as measured by a resolution target (American Society of Photogrammetry 1960). For digital imagery, resolution corresponds to pixel size, and spatial resolution of digital imagery is usually represented in terms of distance (30 meters, 1,000 meters, etc.). The smaller the distance, the finer the resolution of the sensor.

2.6.2. Temporal Resolution

The temporal resolution of a sensor system answers the question: **How often can you “see” an object?** Temporal resolution describes how often the same area on the Earth’s surface is visited by the sensor. This measure applies primarily to satellites whose orbits place them over the same point on the earth’s surface at regular intervals (e.g., 16 and 18 days for the Landsat satellites). Acquisition of airborne remote sensing data, on the other hand, requires special flight planning for each mission. Therefore, if multi-temporal imagery is to be obtained, it will more than likely be obtained at irregular intervals.

2.6.3. Spectral Range and Resolution

Spectral range and resolution answers the question: **For a given sensor, in what parts of the EMS can you receive information?** The spectral range of a sensor system describes its range of sensitivity across the EMS. For example, most photographic films are sensitive only to visible light. IR films are sensitive to both visible and near-IR wavelengths, while thermal-IR sensors are sensitive to longer IR wavelengths and can measure differences in temperature. The spectral resolution of a sensor system, on the other hand, refers to the width of the bands within which the sensor is capable of recording data. Some Earth-orbiting satellites, such as Landsat or SPOT, record data in relatively broad bands that equate roughly to the blue, green, red, and near-IR portions of the EMS. More recently developed hyperspectral scanners are sensitive to very narrow bands and can record data across individual segments of the blue, green, red, or IR portions of the EMS. For example, the Hyperion Instrument is a hyperspectral imager capable of resolving 220 spectral bands between 0.4 and 2.5 µm, spanning the visible, near- and mid-IR portions of the EMS.

2.6.4. Radiometric Resolution

Radiometric resolution answers the question: **How much contrast can you get in remote sensing images?** Radiometric resolution measures a sensor’s ability to distinguish between two objects of a similar reflectance or brightness. The Thematic Mapper (TM), one of the sensor systems aboard the Landsat satellites, has a radiometric resolution of 256. The first Landsat Multispectral Scanners (MSS) had a radiometric resolution of 64 and the later MSS had a radiometric resolution of 128. This means that the TM can identify 256 different brightness or reflectance levels while MSS could only differentiate 64 or 128. TM imagery, therefore, has the higher potential of resolving differences between objects of similar reflectance.
2.6.5. **Is There an Ideal Sensor?**

There is no ideal sensor system in terms of overall resolution. Generally speaking, sensor systems with a high spatial resolution, such as photographic films, will have a low spectral resolution while systems with a high spectral resolution (e.g., Earth-orbiting satellites) will have a low spatial resolution but a higher spectral resolution. Capabilities of individual remote sensing systems must be matched to the information requirements of specific applications.

### 2.7. RELATED OR SUPPORTING TECHNOLOGIES

#### 2.7.1. Navigation Aids

Aircraft navigation aids can provide real-time data on the precise location of an aircraft or other remote-sensing platform, and are helpful for pinpointing targets for which data are desired, especially in remote areas. Early navigation aids were based on receivers that computed location based on signals received from ground-based transmission stations. An example is the **Loran-C** navigation system developed by the U.S. Coast Guard as an aid for maritime navigation but was soon widely used for aircraft navigation. Loran-C units were installed in a number of aircraft flown in USDA Forest Service air operations to facilitate navigation.

The **Global Positioning System** (GPS) is a satellite based positioning system operated by the Department of Defense (DOD). This system was initially designed to provide an accurate, 24 hour, worldwide, all-weather positioning system for military aircraft. Since its implementation, it has been widely used in many forms of navigation (Biggs et al. 1989).

GPS can be thought of as having three components or segments:

- Space segment
- Ground (control) segment
- User segment

The space segment consists of 24 Earth-orbiting satellites, each of which continuously transmit time and navigation signals. The ground segment consists of a network of control and monitor stations that calculate and transmit satellite positions and clock corrections back to the satellites. The user segment consists of a GPS receiver that captures data transmitted by the satellites and computes the latitude and longitude of the receiving station. Most GPS receivers also contain internal software for a variety of standard navigational computations. Although originally designed for military use, GPS has wide applications in civilian aviation, boating and shipping, natural resource management, outdoor recreation, and the automotive industry.

At the present time, GPS receivers available to the civilian sector will obtain locational accuracies ranging from 100 meters to within centimeters of the actual location, depending on the number of satellite signals received, the type of receiver used, the availability of a supplemental differential correction system, and other factors.
GPS receivers can be interfaced with airborne remote sensing systems such as aerial cameras, airborne videographic or digital imaging systems to assist in location of target areas and to provide data on the ground location of the images acquired.

The price of some GPS receivers have reached the point that they are affordable by the general public, and have become a popular consumer item. Today, GPS is widely used by hunters, backpackers, campers, and other outdoor enthusiasts.

2.7.2. Geographic Information Systems

Geographic information systems (GIS) are data storage and manipulation systems that make it possible to maximize use of the spatial information obtained via remote sensing. These systems facilitate storage, manipulation, integration, analysis, and display of spatial data derived either from remote sensing or other sources. GIS consists of computer hardware and software as well as the personnel and operating data that go into the system. In recent years, GIS has become such an integral part of remote sensing that the two disciplines have become virtually inseparable, with GIS being the ultimate repository for data collected by remote sensing.

Spatial information is stored in a GIS as separate data layers or themes. Examples of forest health-related data layers are: vegetation, roads, streams, topography, and location of various forest damage types. These data can be combined or overlayed to form new data layers. Spatial information can be stored in a GIS in a variety of forms, including lines, points, polygons, or pixels. GIS also allows the attachment of attribute labels to identify the data stored in the system.

The analytical products of GIS include maps that show the interrelationships between various spatial features. GIS is also capable of producing tabular summaries or reports. This technology has proven to be a valuable asset in natural resource planning, especially to identify potential areas of conflict or to display the expected results of alternative management scenarios.

In forest health protection, GIS provides a tool for the repository of data on the location of areas of forest damage or areas where the potential for damage in the future is high. GIS also provides for the integration of these data with other data layers that reside in the system to display these locations by landownership class (National Forest, other federal lands, state forest lands, and privately owned lands), vegetation types, topographic features, or political boundaries. Some applications of GIS in forest health protection include:

- Display and reporting of the current status of forest pests and resultant damage.
- Display of areas where forest damage is likely to occur in the future.
- Development of long-term historical databases on location and intensity of forest damage.
- Display of results of actions designed to reduce pest populations.
- Integration of forest health concerns into long-range resource planning.
3. SIGNATURES

This chapter introduces the concept of signatures and the need to recognize signatures of objects of interest in forest health protection. The features that make up signatures of vegetation and vegetation damage, thus making it possible for them to be recognized via remote sensing, are described.

3.1. WHAT IS A SIGNATURE?

In the previous chapter, we have already discussed spectral range and resolution and their importance in detecting visual details of interest. These details of interest are most often biological “signatures.” A **signature** is defined as one or more characteristics used to identify something—an object, a person, etc. A person’s name, written in his or her own handwriting, is the classic example of a signature. Everyone’s handwriting is unique: whether legible or illegible, a person can be identified by their signature, and a signature on an agreement or contract makes it legally binding. Another example of a signature is the theme music used at the beginning of a radio or television program. The tempo and melody of that music, often composed especially for that program, lets the listener identify the program. In the context of forest health protection, entomologists often refer to the gallery patterns left in the cambium layer of trees infested by bark beetles as signatures (Figure 3.1). These patterns are often unique enough to provide a more reliable means of identifying the insect causing the attack than examination of the insect’s life stages.

In remote sensing, signatures are the characteristics or combinations of characteristics that allow an aerial observer, image interpreter or computer aided image analysis system to identify certain objects of interest from a distance. Some characteristics that contribute to the signature of an object observed from a distance and allow it to be identified include:

- Color
- Spectral reflectance (visible light and other regions of the EMS)
- Shape
- Brightness
- Texture
- Spatial position

In the use of remote sensing for forest health protection, it is necessary for forest health specialists to be able to recognize the signatures of certain vegetation types (e.g., conifers versus broadleaf forests versus non forested areas, open versus closed forests, young versus mature forests), tree species and, of course, the characteristics or **symptoms** associated with specific agents that cause forest damage (insects, fire, fungi, air pollution, severe winds), as they appear when seen from low-flying aircraft, on an aerial photograph or a digital image.
Figure 3.1. Galleries etched on the inner bark of trees by bark beetles are often distinct enough signatures to permit identification of the bark beetle species infesting the tree. **Left:** Horizontal egg galleries and fine vertical larval galleries are the classic signature of the fir engraver (*Scolytus ventralis*), a pest of true fir in western North America. **Right:** Winding, “S”-shaped egg galleries with pupal cells are the characteristic signature of the southern pine beetle (*Dendroctonus frontalis*), an important pest of pines in the southeastern United States.
3.2. VEGETATION TYPES AND TREE SPECIES

Recognition of forest or vegetation types is a basic requirement when using remote sensing in forest health protection. Obviously, it is important to know what tree species or species complex is being assessed or affected by a damaging agent. To an experienced aerial observer, identification of forest types is almost second nature. Forest types and tree species can also be discerned by interpretation of aerial photographs or digital images or by computer assisted classification of digital data. Several guides are available to aid in recognition of forest types on aerial photographs (Avery 1966, Sayn-Wittgenstein 1978). An excellent guide to the identification of forest cover types in the New England states on CIR aerial photographs based on color and textural differences is given by Hershey and Befort (1995). Guidelines have been published for identification of tree species on aerial photographs across Canada (Sayn-Wittgenstein 1978) and for several forest regions in the U.S. including conifers in the Northeast (Ciesla 1984), northern Idaho (Croft et al. 1982) the northern Great Lakes (Heller et al. 1964) and northern California and southern Oregon (Ciesla and Hoppus 1990).

3.2.1. Crown Characteristics

The primary crown characteristics used to identify forest vegetation types and tree species by remote sensing are foliage color, shape of the crown apex, crown margin and foliage texture (Heller et al. 1964; Figure 3.2).

Foliage Color - The first characteristic often noticed by an aerial observer or image interpreter, when attempting to identify tree species is differences in foliage color. Subtle differences in the hue and chroma of foliage are often helpful in characterizing individual species. Many of the soft pines indigenous to North America, such as western white pine \((\text{Pinus monticola})\) and eastern white pine \((\text{P. strobus})\), tend to have a blue-green foliage color, in contrast to other conifers, which may have a deep green foliage color (Heller et al. 1964, Croft et al. 1982). Similarly, in the Pacific Northwest, the blue cast to the foliage of noble fir \((\text{Abies procera})\) makes its identification quite easy when viewing forested areas from low-flying aircraft. Some workers (Heller et al. 1964) have used precise definitions provided by Munsell Color Charts to describe foliage color. More recently, more generic terms such as “blue-green, dark-green or olive green” have been found more suitable because of within-species variation in foliage color or subtle differences in image exposure or color balance (Croft et al. 1982, Ciesla and Hoppus 1990).

3.2.1.2. Crown Apex - The shape of the apex or tip of a tree crown, known as crown apex, can vary from the sharp, spire-like crowns of balsam fir \((\text{Abies balsamea})\) and subalpine fir \((\text{A. lasiocarpa})\) to the broad, rounded crowns of many broadleaf trees. Figure 3.2 shows the variety of crown apices.

3.2.1.3. Crown Margin - The outer margin of a tree crown may be smooth or entire, as is the case of some of the cedars \((\text{e.g., Chamaecyparis, Libocedrus, Thuja})\), finely serrate, as is typical of the true firs \((\text{Abies spp.})\), or they may be deeply lobed, typical of the soft or white pines. Crown margins are most helpful in open grown forests where they are not obscured by neighboring trees (Ciesla 1990). Figure 3.2 shows examples of crown margins. Figure 3.3 shows various crown characteristics in an aerial photograph.
3.2.1.4. **Branch Pattern** - Some tree species, such as spruces (*Picea* spp.), and hemlocks (*Tsuga* spp.) have distinct branches when viewed from low-flying aircraft or seen on aerial photographs. Others, such as true firs, have their branches obscured by heavy foliage; therefore, branching is less distinct.

3.2.1.5. **Foliage Texture** - Foliage texture varies between species and is often helpful in species identification. Certain broadleaf trees, such as oaks (*Quercus* spp.), tend to have foliage with a coarse texture when viewed remotely whereas others, such as the birches (*Betula* spp.), tend to have foliage with a finer texture.

Descriptions of the crown characteristics of tree species that occur in a given area can be summarized in tabular form (Table 3.1) or in dichotomous keys (see Figure 4.3 in the Mission Planning chapter), accompanied by either line drawings or photographs to aid aerial observers or image interpreters.

### 3.2.2. Ancillary Information

Knowledge of the site factors that tend to favor the occurrence of certain tree species, such as elevation, aspect, and topographic position, are also helpful in identifying forest types and/or tree species. For example, in the southern Appalachian Mountains, the red spruce (*Picea rubens*)-Fraser fir (*Abies fraseri*) forests are known to occur at elevations above around 5,100 feet above mean sea level (MSL) (Dull et al. 1988). In the northeastern U.S. and Great Lakes regions, eastern larch (*Larix laricina*) and black spruce (*Picea mariana*) are associated with low-lying bogs. In the Rocky Mountains, blue spruce (*Picea pungens*) is usually restricted to riparian zones. Open-grown stands of ponderosa pine (*Pinus ponderosa*) one the other hand, tend to be found on low-elevation, south-facing slopes, while denser forests of Douglas-fir (*Pseudotsuga menziesii*) are found on north-facing slopes. Ancillary information can be integrated with crown characteristics in decision keys to help image interpreters classify forest types or species in localized areas.

### 3.2.3. Sources of Error

Several factors can result in errors in the recognition of tree species’ signatures. Two of the major factors are within species variation and lighting (Ciesla 1990).

**3.2.3.1. Within-species Variation** - The fact that all species of living organisms have variability is a basic tenant of biology. To an individual attempting to identify species or vegetation types, this can be a potential source of error. Douglas-fir, for example, was reported to have a high degree of variability in crown characteristics both in the northern Rocky Mountains (Croft et al. 1982) and in northern California and southern Oregon (Ciesla and Hoppus 1990). Consequently, guidelines for the identification of tree species that do not address the range of crown characteristics for a population of trees may not be effective. Factors that can cause variability in the appearance of tree crowns when viewed remotely include **tree age**, **stress**, and **site** conditions (Ciesla 1990).
Figure 3.2. Tree crown apices (A) and margins (B) (redrawn from Heller et al. 1964).
Figure 3.3. Section of a color aerial photograph taken over a portion of the Siskiyou National Forest, Oregon, showing crown characteristics helpful in identifying three tree species: Douglas-fir, western hemlock, and Port-Orford cedar (original scale = 1:4,000).

Table 3.1. Crown characteristics of major conifers occurring in New Hampshire, northern New York and Vermont helpful in species identification on 1:8,000-scale CIR aerial photographs (Ciesla 1984b).

<table>
<thead>
<tr>
<th>Species</th>
<th>Crown Type</th>
<th>Crown Apex</th>
<th>Crown Margin</th>
<th>Foliage Texture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red or black spruce (Picea rubens, P. mariana)</td>
<td>Broadly conical</td>
<td>Obtuse</td>
<td>Lobed</td>
<td>Medium</td>
</tr>
<tr>
<td>Balsam fir (Abies balsamea)</td>
<td>Narrowly conical</td>
<td>Acute/Accuminate</td>
<td>Finely serrate</td>
<td>Fine</td>
</tr>
<tr>
<td>Eastern hemlock (Tsuga canadensis)</td>
<td>Broadly conical</td>
<td>Obtuse</td>
<td>Sinnuate</td>
<td>Fine</td>
</tr>
<tr>
<td>Eastern white pine (Pinus strobus)</td>
<td>Irregular, horizontal branching</td>
<td>Broadly rounded</td>
<td>Lobed/parted</td>
<td>Medium</td>
</tr>
<tr>
<td>Red pine (Pinus resinosa)</td>
<td>Open, rounded</td>
<td>Broadly rounded</td>
<td>Finely serrate</td>
<td>Course</td>
</tr>
<tr>
<td>Eastern larch (Larix laricina)</td>
<td>Narrowly conical</td>
<td>Acute</td>
<td>Finely serrate</td>
<td>Fine</td>
</tr>
<tr>
<td>Northern white cedar (Thuja occidentalis)</td>
<td>Oval</td>
<td>Broadly rounded</td>
<td>Entire/ sinnuate</td>
<td>Medium</td>
</tr>
</tbody>
</table>
Young trees (seedlings, saplings and poles) tend to have a higher reflectance in the near-IR region than do their older counterparts. Therefore, they will appear as a brighter red on CIR films. In Germany, foresters have found that sapling-size Norway spruce (*Picea abies*) will be a brighter red color on CIR film than mature trees of the same species (Grundman 1984). Similarly, young Fraser fir (*Abies fraseri*) in the southern Appalachian Mountains tend to appear brighter red than older Fraser fir (Ciesla et al. 1986).

Older trees tend to have more distinct branches than their younger counterparts. Douglas-fir in southwestern Oregon tends to have a partially distinct, layered pattern to their branches up to about age 100, when viewed on large- and medium-scale color aerial photographs. Older individuals may have a more distinct branch pattern, which could be confused with the signature typical of western hemlock (*Tsuga heterophylla*) (see Figure 3.3). Large, old true firs occurring in the same area tend to exhibit a similar pattern (Ciesla 1990, Ciesla and Hoppus 1990). Fraser fir on high-elevation sites in the southern Appalachian Mountains tend to have more distinct branches as they get older, giving them the appearance of an inverted cone when viewed on vertical aerial photographs. This makes them more difficult to separate from neighboring red spruce, a tree that characteristically has a distinct branching pattern in all age classes (Ciesla et al. 1986).

The presence of insects, disease or other agents that cause tree stress and/or damage, the very thing that forest health specialists are seeking from remote sensing data, can alter foliage color, crown form, and branching pattern of trees, and can significantly affect the ability of even the most experienced aerial observer or photo-interpreter to make correct species identifications.

Trees growing at low elevations, where soils tend to be relatively deep and growing conditions relatively good, often have different crown forms than their high-elevation counterparts. High-elevation trees typically have slower growth rates due to shorter growing seasons, and are subject to frequent episodes of high winds. In the northeastern U.S. and adjoining portions of Canada, balsam fir (*Abies balsamea*) growing at low elevations have a narrow, conical crown. Here, this tree is relatively easy to distinguish from red and white spruce (*Picea rubens* and *P. glauca*), with which it is often associated. At high elevations, both species are affected by high winds: this alters the appearance of the crowns of both species, making them more difficult to identify.

3.2.3.2. **Tree Position and Lighting** – The position of a tree crown on an aerial photograph can change its appearance. Trees on the edge of an aerial photograph will tend to be partially oblique instead of vertical especially if photos are taken with a short focal length lens at large scales. Consequently many of the described crown characteristics, which assume a vertical image, will not be as useful. A tree on a shaded slope will appear darker than on a well-lit slope. “Vignetting,” a common phenomenon when using short focal length lenses to acquire aerial photographs at large scales, can cause a similar problem at the outer edges of an aerial photograph. Tree species identification is best done near photograph center and on optimally exposed portions of an aerial photograph.

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1See chapter 6, section 6.6.3, for a detailed discussion of color infrared film.
3.2.4. Stand Characteristics

Two stand characteristics of potential interest in forest health assessment, which can be evaluated on some remote sensing products, are crown diameter and crown closure. Crown diameter can be used as an indicator of stand size class and to determine if the stand is even-aged or contains several age classes. Crown closure, on the other hand, is a measure of stocking levels or stand density, and has value as a tool for pest hazard rating or to identify stands in need of thinning. Both of these characteristics can be estimated on aerial photographs using clear plastic crown diameter or crown density scales (see chapter 6, section 6.9.2; Avery 1966).
3.3. **FOREST DAMAGE**

Detection, mapping and assessment of damage caused by agents such as insects, fungi, air pollution and severe winds is the primary use of remote sensing in forest health protection. Certain types of forest damage, such as tree mortality or foliar injury, are highly visible and can be seen from low-flying aircraft, on aerial photographs and even, in a few cases, on images produced from digital data obtained from Earth-orbiting satellites. Other damage, such as localized feeding injury to the shoots or leaders of trees, is more subtle and not easily resolved via remote sensing.

3.3.1. **The Nature of Forest Damage**

Forest damage is dynamic and subject to change from one year to the next and even within a single growing season. Insect outbreaks can appear over extensive areas of forest within a year in places where there was little or no evidence of their presence during the previous year. Within a growing season, the appearance of damage is tied to the life history of the damaging agent. The characteristic red-brown color indicative of defoliation by spruce budworms (*Choristoneura* spp.), for example, generally begins to appear in mid-summer, as the larval mature and are ready to enter the pupal stage. Moreover, as the season progresses and the damaged needles drop from the infested trees, the damage becomes less conspicuous and more difficult to resolve. In the case of defoliating insects of broadleaf forests, such as gypsy moth (*Lymantria dispar*) damaged trees typically put out a second crop of foliage. This masks the defoliation within one to two weeks after it has reached its peak. Consequently, the acquisition of data on forest damage, whether by remote sensing or ground methods, is often time-sensitive, and narrow biowindows define the optimum time that the data must be acquired.

Most forest damage first appears as a change of color of the forest canopy. The foliage of trees killed by bark beetles, sucking insects or certain root fungi changes from green to yellow or red. In the vernacular of the forest health specialist, this process is referred to as *fading* and dying trees, especially conifers, are called *faders*. Forests suffering from defoliation by insects take on a red-brown or gray hue. The ability to detect subtle changes in the color of the forest canopy is a key requirement when using remote sensing techniques to detect or map forest damage. Therefore, aerial observers engaged in mapping forest damage must be capable of seeing the full spectrum of colors. Similarly, black-and-white panchromatic aerial films, which are widely used in many engineering and natural resource applications, have little or no value for assessment of forest damage.

The following sections provide descriptions of various forest damage signatures. While it may not be necessary to map all of these damage types during forest health assessments, it will be necessary to recognize them so that those of concern can be distinguished from those that are not of concern.
3.3.2. Tree Mortality

3.3.2.1. Bark Beetles - Coniferous bark beetles (Coleoptera: Scolytidae) are among the most destructive insect pests of North American forests. Bark beetle infestations are characterized by the occurrence of groups of dead and dying trees, ranging from five to several thousand trees, or as a scattering of tree mortality. The color of the fading trees and the pattern of tree mortality is distinct enough to most of the major bark beetle species to permit reasonably accurate identification of the causal insect by aerial observation.

In the southeastern United States, pine forests (e.g., Pinus taeda, P. echinata, P. virginiana, etc.) are subject to periodic outbreaks of the southern pine beetle (Dendroctonus frontalis). Tree-killing by this insect is characterized by the presence of distinct groups or “spots” of dead and dying trees. This insect can have from three to seven generations per year, with multiple overlapping generations remaining in a single spot. Therefore, the fading trees in a southern pine beetle spot often have a color gradient ranging from red to yellow to pale green, with the longest-attacked trees being dark red-brown in color and the most recently attacked trees being yellow or pale green. Beyond the area of visible tree mortality, there could be additional green infested trees. Smaller southern pine beetle spots, those consisting of around 100 or fewer trees, typically contain one active “head” as indicated by the presence of trees with yellow and pale green crowns (Figure 3.4). Sometimes this insect will cause exceptionally large spots of several thousand trees. Under these conditions, there may be several active heads in a single spot (Figure 3.5). The pattern and color of tree fading caused by southern pine beetle does not vary by host species attacked.
Another group of tree killing bark beetles present in the eastern United States are the pine engraver beetles (*Ips* spp.). Three species of *Ips*—*I. avulsis*, *I. grandicollis*, and *I. calligraphus*—are capable of causing small group kills in southern pines. These insects are sometimes associated with southern pine beetle, but may also be found attacking trees by themselves. The pine engraver (*I. pini*) attacks both pines and spruces in the northeastern, central, and western United States and adjoining portions of Canada. Groups of trees killed by engraver beetles rarely exceed 20-50 trees in size. Both *I. avulsis* and *I. pini* can confine their attacks to the upper half or third of a tree, causing fading of only a portion of the crown. *Ips* engraver beetles frequently make their initial attacks in fresh down material, and later attack standing trees, especially during periods of dry weather. The occurrence of groups of dead and dying pines near pulpwood decks at railroad sidings or in the immediate vicinity of log yards, portable sawmills, etc. is a clue that the tree mortality is being caused by this group of insects and not pine-infesting species of *Dendroctonus*.

In the western United States, several coniferous bark beetles are major pest problems. Their signatures can often differentiated by the color of the fading trees and the attack pattern (Table 3.2). Ponderosa pines attacked by mountain pine beetle (*Dendroctonus ponderosae*) fade to a yellow-green to pale yellow-orange color (sorrel) one year after they have been attacked. During the following season, the foliage turns to a red-brown hue and during certain months it is possible to distinguish between two seasons’ attacks (Figure 3.6). When mountain pine beetle attacks occur in lodgepole pine (*Pinus contorta*) trees fade to a bright red-orange color one year following attack (Figure 3.7). Therefore, mountain pine beetle attacks in ponderosa and lodgepole pines can be easily differentiated simply by the difference in the color of the fading trees (Figure 3.8). When western white pine (*P. monticola*) or sugar pine (*P. lambertiana*) are attacked by mountain pine beetle, they fade to a red or red-brown color.
Table 3.2. Aerial characteristics of bark beetle caused tree mortality in western North America helpful in identification of causal insect.

<table>
<thead>
<tr>
<th>Bark beetle</th>
<th>Host (s)</th>
<th>Foliage color of current year’s faders</th>
<th>Mortality pattern</th>
<th>Other characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mountain pine beetle, <em>Dendroctonus ponderosae</em></td>
<td>Ponderosa pine</td>
<td>Yellow-green to yellow orange (sorrel)</td>
<td>Scattered or group kills of up to 200 trees</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lodgepole pine</td>
<td>Bright rust red</td>
<td>Scattered or small groups widespread mortality over large areas</td>
<td></td>
</tr>
<tr>
<td></td>
<td>W. white &amp; sugar pines</td>
<td>Rust red</td>
<td>Single trees or small group kills</td>
<td></td>
</tr>
<tr>
<td>Pine engraver beetles, <em>Ips</em> spp</td>
<td>Ponderosa pine</td>
<td>Yellow-green to yellow orange (sorrel)</td>
<td>Scattered or small group kills (&lt;50 trees)</td>
<td>Fading of upper $\frac{1}{4}$ - $\frac{1}{2}$ crown may be apparent on some trees, especially along edges of spot.</td>
</tr>
<tr>
<td>Western pine beetle, <em>Dendroctonus brevicomis</em></td>
<td>Ponderosa pine</td>
<td>Yellow-green to yellow orange (sorrel)</td>
<td>Scattered, (young stands) group kills (older stands)</td>
<td></td>
</tr>
<tr>
<td>Jeffrey pine beetle, <em>Dendroctonus jeffreyi</em></td>
<td>Jeffrey pine</td>
<td>Yellow-green to yellow orange (sorrel)</td>
<td>Scattered or small group kills (±20 trees)</td>
<td></td>
</tr>
<tr>
<td>Douglas-fir beetle, <em>Dendroctonus pseudotsugae</em></td>
<td>Douglas-fir</td>
<td>Off-green, yellow or red</td>
<td>Scattered or group kills of up to 100 trees</td>
<td></td>
</tr>
<tr>
<td>Spruce beetle, <em>Dendroctonus rufipennis</em></td>
<td>White spruce (Alaska) Engelmann spruce (Rocky Mtns)</td>
<td>Pale yellow (straw) pale green*</td>
<td>Group kills or widespread mortality over large areas</td>
<td>In some areas, e.g., northern Rockies and E. Oregon, spruce is found in riparian zones</td>
</tr>
</tbody>
</table>
Table 3.2 (continued). Aerial characteristics of bark beetle caused tree mortality in western North America helpful in identification of causal insect.

<table>
<thead>
<tr>
<th>Bark beetle</th>
<th>Host(s)</th>
<th>Foliage color of current year’s faders</th>
<th>Mortality pattern</th>
<th>Other characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fir engraver, <em>Scolytus ventralis</em></td>
<td>True firs</td>
<td>Red-orange</td>
<td>Scattered trees or small group kills (generally &lt; 100 trees)</td>
<td>Branch fading or fading of upper $\frac{1}{4} - \frac{1}{2}$ crown may be apparent on some trees</td>
</tr>
<tr>
<td>Western balsam bark beetles, <em>Dryocoetes spp.</em></td>
<td>True firs</td>
<td>Red-brown</td>
<td>Scattered</td>
<td>Generally found in high-elevation forests</td>
</tr>
</tbody>
</table>

*The foliage of spruce often drops from bark beetle attacked trees as it fades.

Figure 3.6. Ponderosa pine killed by mountain pine beetle, Black Hills National Forest, South Dakota. Note color differences (light yellow for current-years’ faders and red-brown for two-year-old faders) between two years of attacks.

Fig 3.7. Lodgepole pine killed by mountain pine beetle on the Montana-British Columbia border.
Western pine beetle (*D. brevicomis*) is a pest of ponderosa pine, primarily in California, Oregon, Idaho, and western Montana. Ponderosa pines attacked by this insect fade to the same color as do ponderosa pines attacked by mountain pine beetle. This insect typically attacks large ponderosa pines, and sometimes a determination of the insect responsible for the attack can be made on the basis of tree size. When attacks occur in small, second-growth ponderosa pines, it is virtually impossible to distinguish between mountain pine beetle and western pine beetle attacks.

At least two signatures characterize Douglas-fir beetle (*Dendroctonus pseudotsugae*) attacks in Douglas-fir. On the western slopes of the Cascades and in northern Idaho, distinct groups of trees are typically killed. There is often a mixture of colors present, especially in the early stages of fading when trees with off-green, yellow, and red foliage can be seen (Figure 3.9). Under drier, “east side” conditions, Douglas-fir beetle infestations often consist of a scattering of dead and dying trees, and the trees typically fade to a red or red-brown color (Figure 3.10).

Tree mortality caused by the spruce beetle (*Dendroctonus rufipennis*) is one of the more difficult signatures to detect. In the case of Engelmann spruce (*Picea engelmannii*), the foliage of infested trees often dries and falls from the trees before fading occurs. In Alaska, the foliage of spruce beetle infested white spruce (*P. glauca*) turns a pale straw yellow color before it drops from the tree (Figure 3.11).
Figure 3.9. Douglas-fir beetle (*Dendroctonus pseudotsugae*) infestation, Nezperce National Forest, Idaho.

Figure 3.10. Scattered tree mortality caused by Douglas-fir beetle, Roosevelt National Forest, Colorado.
Figure 3.11. Mortality of white spruce caused by spruce beetle, *Dendroctonus rufipennis*, on the Kenai Peninsula, Alaska.

The signature of tree mortality caused by the fir engraver in grand fir (*Abies grandis*) in Idaho, Oregon and Washington consists of either groups or scattered trees that fade to a bright red-orange color (Figure 3.12). A similar pattern occurs on white fir (*A. concolor*) in California, but since white fir is often an understory tree, fading trees are sometimes difficult to see. Tree killing caused by western balsam bark beetles (*Dryocoetes confusus*) is characterized by a scattering of dead and dying trees. Color of fading trees is red to red-brown (Figure 3.13).

### 3.3.2.2. Balsam Woolly Adelgid

Balsam woolly adelgid (*Adelges piceae*) (Homoptera: Adelgidae), is a sucking insect accidentally introduced into North America from Europe. This insect infests the mainstem and branches of true firs and causes deformity and tree killing. Several North American species of *Abies* are highly sensitive to the feeding of this insect. One of the most sensitive is the Fraser or southern balsam fir (*Abies fraseri*), which is endemic to the high peaks of the southern Appalachian Mountains. Tree mortality in Fraser fir, indicative of balsam woolly adelgid infestation, is characterized by a scattering of dying trees with bright red-orange foliage. The presence of trees with a fading lower crown and a green upper crown is a signature unique to attack by this insect (Lambert and Ciesla 1966).

### 3.3.2.3. Root Disease

Various root diseases such as those caused by the fungi *Heterobasidium annosum*, *Phellinus weirii*, and *Armillaria* spp. kill host trees in distinct centers much in the way trees are killed by bark beetles. The action of root disease is much slower, however. Therefore, the signatures of root disease are often characterized by the presence of a scattering of dead trees and an occasional fader. These can sometimes be seen on aerial photographs, but are more difficult to detect from low-flying aircraft. Centers of tree mortality in pine plantations due to annosus root rot, caused by *Heterobasidium annosum*, have been resolved on large-scale aerial photographs (Hadfield 1970, Hanson and Lautz 1971, Murtha and Kippen 1969).
In northern Idaho, root disease centers are characterized by the presence of openings in the forest canopy. These can be seen on CIR aerial photographs. The openings consist of a few conifers tolerant to root disease, some reproduction, brush cover near the center of the opening and dead or dying trees near the perimeter of the opening Williams (1973).

An exception to the conditions described in the preceding paragraphs is a root disease of Port-Orford cedar (Chamaecyparis lawsoniana), a highly valued tree whose natural range is restricted to portions
of southwestern Oregon and northern California. The disease is caused by the fungus *Phytophthora lateralis*. Trees infected by *P. lateralis* die rapidly and fade to a pale orange color, a signature highly visible from long distances. The spores of this fungus are spread by water; consequently, trees growing near streams are most likely to become infected. The presence of pale orange faders concentrated along the edges of streams is a classic signature of infection by this fungus (Figure 3.14).

![Figure 3.14. A classic signature of tree mortality of Port-Orford cedar root disease caused by the fungus *Phytophthora lateralis* on the Siskiyou National Forest, Oregon, consisting of pale orange faders concentrated along a stream (in the upper left-hand portion of the photograph).](image)

3.3.2.4. Oak Wilt - Oak wilt, a vascular disease caused by the fungus *Ceratocystis fagacearum*, kills various species of oaks in the eastern United States. The foliage of many species of infected and dying oaks, especially the red oaks, first turns a dull green or bronze color and has a water-soaked appearance. Later, the foliage turns yellow or brown as the tree dies (Rexrode and Brown 1983). Oak wilt infection centers have been detected by forest pathologists via aerial surveys in many parts of the natural range of this disease (Lautz and Saufley 1970, Peacher et al. 1975) and studies in eastern Tennessee showed that symptoms of oak wilt could be detected on both color and CIR films at scales of 1:4,000 (1:3,960) and 1:8,000 (1:7,920) (Roth et al. 1963).

One of the most widespread occurrences of this disease is in central Texas where Texas live oak (*Quercus fusiforme*) is infected. Texas live oak occurs in pure stands, which are the result of sprouting from a common root system (Billings et al. 1982). Consequently, when a tree becomes infected, the fungus spreads through the root system, ultimately infecting the entire stand. The signature of dead groups of live oak infected by oak wilt can be seen from low-flying aircraft and on CIR aerial photographs (Figure 3.15) (Ciesla et al. 1984a).
3.3.2.5. Tree Mortality Caused by Defoliating Insects - Several years of successive defoliation by insects is known to cause widespread tree mortality. Sometimes insect caused tree mortality can be confused with current year’s defoliation, especially on small-scale aerial photographs. Guidelines for differentiating between tree mortality and defoliation caused by gypsy moth on CIR aerial photographs taken over eastern broadleaf forests are given by Ward et al. (1986) as follows:

Defoliation:

1. Often widespread, covering large areas.
2. Pattern of discoloration is relatively uniform.
3. Edges of defoliated areas tend to be somewhat indistinct or blurred.

Tree Mortality:

1. Usually more localized.
2. Pattern of discoloration tends to be less uniform. Often, there is a mottled appearance due to the presence of holes with dead trees in an otherwise uniform canopy of living trees.
3. Edges of mortality areas tend to be more distinct.
3.3.3. Foliar Injury

Many types of foliar injury are visible from long distances and lend themselves to assessment via remote sensing. Examples include defoliation, skeletonizing, and mining of foliage by insects, chlorotic foliage due to nutrient deficiencies or other stress, and necrosis due to exposure to chemical pollutants.

3.3.3.1. Insect Damage - Mapping and assessment of damage caused by foliage feeding insects is one of the most widely used applications of remote sensing in forest health protection. Both conifers and broadleaf trees are subject to periodic outbreaks of defoliating insects, which appears as a red-brown or gray discoloration of the forest canopy.

In the case of conifers, successive years of defoliation results in cumulative damage, sometimes making it difficult to separate the current year’s damage from damage caused in previous years. This is especially true of feeding by both eastern and western spruce budworms (*Choristoneura fumiferana*) and (*C. occidentalis*). Larval feeding is restricted to the current year’s buds and shoots (Figure 3.16). During the first year of defoliation, this appears as a slight reddish brown discoloration or “halo” against a backdrop of green foliage (Figure 3.17). After three to four successive years of feeding, damaged forests tend to take on a gray cast, and it is critical to map the current year’s feeding during the time that the red-brown discoloration of the current year’s feeding remains on the damaged trees (Figure 3.18). The same is true of the Douglas-fir tussock moth (*Orgyia pseudotsugata*) a defoliator of western Douglas-fir and true fir forests. This insect, however, is capable of feeding on both the current and previous year’s foliage, and can strip a tree of all of its foliage in a single growing season. Therefore, defoliation by Douglas-fir tussock moth can sometimes be recognized, or at least suspected, by the occurrence of heavy defoliation in areas where no damage was detected during the previous year (Figure 3.19).

An exception to the cumulative effect of feeding injury on conifers is defoliation on larches (*Larix* spp.), which are deciduous. Feeding by larch casebearer (*Coleophora laricella*), an introduced leaf miner of larches, appears as a yellow to yellow-orange discoloration of the tree crowns, and all of the visible feeding damage is due to the current generation of insects (Figure 3.20). This insect has caused severe damage to western larch (*Larix occidentalis*) a component of forests in western Montana, northern Idaho, and eastern Oregon and Washington.
Figure 3.16. Feeding injury by western spruce budworm, *Choristoneura occidentalis* occurs only on the current year’s buds and shoots (Mt. Mood National Forest, Oregon).

Figure 3.17. Early stages of spruce budworm defoliation on subalpine fir (Clearwater National Forest, Idaho).

Figure 3.18. Gray cast to forest canopy caused by several years of successive defoliation by western spruce budworm (Mt. Hood National Forest, Oregon).
Figure 3.19. Defoliation of Douglas-fir by Douglas-fir tussock moth near Missoula, Montana.

Figure 3.20. Defoliation of western larch by larch casebearer, Colville National Forest, Washington.

Insect-caused defoliation in deciduous broadleaf forests generally appears as a red-brown or gray discoloration of the forest canopy. Often the most severe defoliation is found on the crests of ridges. In most cases the signature of forest defoliators as seen via remote sensing is similar regardless of the species involved (Figure 3.21). Determination of the insect or insect complex causing the damage must be made by ground visits to damaged sites or from data collected during previous field seasons.
Other types of insect-caused foliar injury such as leaf mining or skeletonizing are also visible via remote sensing. An excellent example is the skeletonizing of the underside of the leaf surface caused by the locust leaf miner (*Odontota dorsalis*) on black locust (*Robinia pseudoacacia*), causing a red-brown discoloration of the foliage (Figure 3.22). Although not considered to be a major forest pest, the late-summer-feeding injury caused by this insect is highly visible.

3.3.3.2. Foliar Injury from Air Pollution, Exposure to Chemicals or Other Abiotic Factors - Many pollutants exist in our environment. Three pollutants known to affect forests are ozone (*O₃*), sulfur dioxide (*SO₂*), and hydrogen fluoride (*HF*) (Jacobson and Hill 1970, Skelley et al. n.d.). Each produces symptoms that allow reasonably reliable identification of the causal factor. Exposure to ozone, for example, can cause a chlorotic mottling (Figure 3.23), tip burn and purple discoloration, depending on the host plant affected and the severity and duration of exposure. *SO₂* can cause a tip necrosis on conifers and an interveinal necrosis on broadleaf species. Exposure to high levels of hydrogen fluoride causes tip burn or tip necrosis on both conifers and broadleaf species.
Symptoms or signatures of air pollution are sometimes severe enough to be visible from the air, especially in forests near industrial sources or near sites of accidental spilling or burning of chemicals. The appearance of foliar discoloration near these sites on a number of plant species should cause aerial observers or image interpreters to suspect air pollution or exposure to chemicals as a possible factor, one that requires further investigation. Heavy concentrations of human population in basins surrounded by high mountains, where motor vehicle exhausts and other pollutants are trapped, exposed to sunlight, and result in high concentrations of ozone are another situation in which air pollution can cause extensive forest damage. The Los Angeles and Mexico City Basins are excellent examples of the latter phenomenon (see Figure 3.23).

In many instances, forest damage caused by air pollution is accompanied by high levels of damage by insects or diseases that attack trees weakened by exposure to the pollutant. This is especially true in conifer forests where trees stressed by long term exposure to air pollution may be subject to attack by bark beetles.

### 3.3.4. Diebacks and Declines

Diebacks and declines are complex conditions that could involve one or a number of causal factors including site, exposure to chemicals, drought or other climatic anomalies, insects, and pathogens. An excellent review of this group of diseases is presented by Manion (1991). Many diebacks and declines are the result of a complex interaction of both biotic and abiotic factors including long-term predisposing factors, short-term inciting factors, and long-term contributing factors. Symptoms of diebacks and declines are varied, and include chlorotic or yellow foliage, crown thinning, branch dieback, early fall coloring, stunted or dwarfed foliage, and sometimes, tree mortality. Many of these symptoms can be seen via remote sensing.
Figure 3.23. Signatures of air pollution damage. **Upper:** Aerial view of damage to Douglas-fir caused by exposure to SO$_2$ near Missoula, Montana. **Lower left:** Chlorotic mottling of foliage of *Pinus hartwegeii* near Mexico City, Mexico. **Lower right:** Ponderosa pine with symptoms of exposure to high levels of ozone, San Bernadino National Forest, California.

Beech bark disease is an example of a classic decline. In North America, this condition occurs when the bark of American beech (*Fagus grandifolia*) becomes infested by an insect known as the beech scale (*Cryptococcus fagisuga*). This insect was accidentally introduced into North America from Europe around 1890. Insect feeding causes a drying and cracking of the bark. This provides openings that can be invaded by fungi, primarily *Nectria coccinea* var. *faginata* and occasionally *N. galligena* (Houston and O’Brien 1983). Beech bark disease produces a characteristic signature when viewed from the air or on large- to medium-scale aerial photographs and consists of a scattering of trees with yellow crowns, branch or top dieback, and dead trees (Figure 3.22). Other decline conditions that produce aerially visible signatures in North American forests include oak decline, maple decline, birch dieback, and ash dieback.

### 3.3.5. Climatic Events

Climatic events such as hurricanes, tornadoes, ice storms, and microbursts can result in sudden, widespread damage to forests (Figure 3.24). For example, in October 1997, a microburst caused
severe winds on the western slopes of the Mt. Zirkel Range of the Routt National Forest and resulted in windthrow of old growth Engelmann spruce on some 20,000 acres. In January 1998, a severe ice storm damaged forests in portions of Maine, New Hampshire, northern New York, Vermont, and adjoining parts of Canada (USDA Forest Service 1998b). This storm caused a wide range of damage, including crown breakage, and bent and broken main-stems. Forest damage from catastrophic climatic events is highly visible, and can be mapped from low-flying aircraft and aerial photographs.

![Figure 3.24. Examples of forest damage caused by climatic events. Upper left: Windthrow in longleaf pine forest due to a severe hurricane, DeSoto National Forest, Mississippi. Upper right: Damage to Engelmann spruce and other conifers caused by a severe storm, Routt, National Forest Colorado. Lower left: Damage caused by a severe ice storm, White Mountain National Forest, New Hampshire. Lower right: Fir waves in high-elevation balsam fir forest, Lookout Mountain, Adirondack Mountains, New York.](image)

Mature, even-age, high-elevation forests of balsam fir in the eastern U.S. and Canada are subject to a phenomenon known as “fir waves” or “regeneration waves.” These are bands of tree mortality that occur generally parallel to the contour of the slope. The dieback gradually progresses up the slope. Sometimes several more or less parallel bands of waves can be seen on the same slope. A new stand
of balsam fir regenerates in areas where the trees have been killed. Fir waves are believed to be an integral part of the dynamics of high-elevation balsam fir forests, and are triggered by cold winds striking exposed forest margins (Sprugel 1976, Sprugel and Borman 1981). Fir waves are a distinct signature that can be seen from viewpoints, low-flying aircraft, and on aerial photographs (see Figure 3.24).

Red belt is another type of forest damage driven by a climatic anomaly and is a fairly common winter phenomenon on western conifers, especially on lodgepole pine. This condition occurs when warm chinook winds buffet south and west facing mountain slopes, causing the needles to dessicate (Manion 1991). The root systems, which are frozen, are unable to replenish the lost moisture. This signature is visible from long distances, and appears as distinct bands of conifers with bright red foliage at certain elevation zones.

### 3.3.6. Parasitic Plants

Dwarf mistletoes (*Arceuthobium* spp.) are parasitic on many North American conifers and are considered important disease pests (Hawksworth and Wiens 1996). Dwarf mistletoe infections cause a range of symptoms, including growth loss, witches brooms (Figure 3.25), dieback, and tree mortality. Symptoms associated with some species of dwarf mistletoe can sometimes be seen from low-flying aircraft and have been resolved on aerial photographs.

Infection centers, as indicated by presence of witches brooms and/or centers or tree mortality caused by two species of dwarf mistletoe, *A. americanum* on jack pine (*Pinus banksiana*) and *A. pusillum* on black spruce (*P. mariana*) have been mapped with varying degrees of success using both aerial sketchmapping and aerial photographs (Baker et al. 1992, Meyer and French 1966, Walters and Munson 1981). In western North America, lodgepole pine forests with heavy dieback and tree mortality due to infection by *A. americanum* sometimes tend to have a gray cast that is visible from small aircraft (Figure 3.25).
Figure 3.25. **Upper left:** Large witches broom caused by the dwarf mistletoe (*Arceuthobium pusillum*) on black spruce (*Picea mariana*), Superior National Forest, Minnesota. **Upper right:** Eastern dwarf mistletoe infection on black spruce, Superior National Forest, Minnesota. **Below:** Aerial view of dwarf mistletoe infested lodgepole pine forest on the Routt National Forest, Colorado; gray cast is due to dieback and tree mortality (photograph courtesy of Dave Johnson, USDA Forest Service, Lakewood, Colorado).
3.4. **NOXIOUS WEEDS**

Noxious weeds are plants with undesirable attributes, such as toxicity to livestock or having the capacity to invade sites and displace forage or other more favored vegetation. Many noxious weeds have been accidentally introduced into North America and, in the absence of natural enemies that regulate populations in their native habitats, have spread over large areas of rangelands, woodlands and forests. Examples of exotic noxious weeds of concern in the western U.S. include yellow starthistle (*Centaurea solstitialis*), spotted knapweed (*C. maculosa*), rush skeletonweed (*Chondrilla juncea*), and leafy spurge (*Euphorbia esula*). All have been introduced from Europe or Eurasia.

The noxious weed problem is increasing in the United States and in recent years there has been an increased interest in management of these pests. Ground surveys to detect and map the location of infested areas are costly and time-consuming, and there has been interest in mapping and monitoring noxious weeds via remote sensing. Successful recognition of noxious plants on aerial photographs or other remote sensing data is based on a combination of plant signatures and knowledge of their habitat requirements.

As is the case with detection of forest damage, the acquisition of data on many noxious weeds is time-sensitive. Opportunities to successfully map the location of weed infested sites may occur during periods of peak flowering or fall coloring. Leafy spurge, for example, produces conspicuous yellow flowers in late spring and early summer. Moreover, the foliage of some leafy spurge plants turns a characteristic rusty orange color in early fall, and provides good contrast to the surrounding straw-colored cured grasses and other vegetation (Figure 3.26). Presence of grey, standing dead plant stems are a signature indicative of the presence of both yellow starthistle and spotted knapweed on color aerial photographs (Lake et al. 1997).

Another factor to consider in mapping of noxious weed populations using remote sensing is the occurrence of plants that have a signature similar to the plant of interest resulting in commission error (chapter 4, section 4.3.1.2). For example, the latter part of the peak flowering period of leafy spurge overlaps with that of the flowering of yellow sweet clover (*Melilotus officinalis*) (Figure 3.27), another introduced plant that covers large areas of rangeland but is not considered noxious. Both plants produce yellow flowers, and would be differentiate to separate on aerial photographs or other sensor products.

Foliage characteristics can also result in distinct signatures helpful in identifying certain noxious weeds. Texas lantana (*Lantana horrida*), a noxious weed native to east Texas and adjoining portions of Mexico, has foliage with an upper surface covered with a thick, silvery pubescence. This increases its spectral reflectance values in both the visible and near-IR regions, and causes the plant to appear as a bright pink color on large-scale (1:500 and 1:1,000) CIR aerial photographs, allowing it to be distinguished from plants with which it is associated. Acquisition of data to detect and map *L. horrida* infestations must take place during periods of flush foliage development because this plant becomes deciduous during periods of soil-water stress (Everitt et al. 1984).
Figure 3.26. Characteristics of leafy spurge that lend themselves to possible detection by remote sensing. **Upper left:** Close-up of flower. **Upper right:** Infested rangeland near Ft. Collins, Colorado, at peak bloom. **Below:** Rusty red color of foliage in autumn.
Other species of invasive plants have other qualities that simplify or complicate efforts to survey them remotely. *Melaleuca quinquenervia*, a woody invasive weed that has become established and is now widely distributed in the Everglades National Park, Florida, is large enough to be easily detected on large-scale CIR aerial photographs (McCormick 1999). Other noxious weeds, such as rush skeleton weed, which has thin, stalky stems, do not produce a distinctive signature, and are not good remote sensing targets (Lake et al. 1997).

Ancillary data (such as cover type, elevation, aspect, and slope, stored in a GIS) can be used to model and identify habitats that are suitable for certain noxious weeds (Lake et al. 1997). This information can be used to identify sites with a potential for harboring noxious weed populations and to target sites for surveys.
4. MISSION PLANNING, DATA COLLECTION, AND ACCURACY ASSESSMENT

The objective of remote sensing, regardless of the application, is to provide qualitative and quantitative data to support decisions in forest management. This chapter discusses some of the basic processes required to plan, design and collect data of interest in forest health protection using available remote sensing tools. Chapters 5 through 10 present specific examples of these processes as they relate to various remote sensing tools of interest in forest health protection.

4.1. MISSION PLANNING

Obviously the first logical step of any activity is planning. Some of the key issues to be considered when planning a forest health protection related remote sensing mission include:

- Objectives and data requirements,
- Biowindows,
- Weather conditions,
- Classification standards, and
- Area coverage.

4.1.1. Objectives and Data Requirements

The first step in the planning process is to define the objectives of the mission. The purpose of the proposed assessment should be clearly defined. Logical objectives for forest health-related assessments involving remote sensing include:

- Mapping location and intensity of damage,
- Stand hazard rating,
- Assessment of impacts and resource losses, and
- Evaluation of treatment effects.

With a clearly defined objective in hand, the next step is to identify the data requirements. In defining data requirements, several basic questions should be addressed:

- What is the area of concern?
- What information is needed?
- What levels of accuracy are required?
- When are the data needed?
- How should the information be presented?

The area to be assessed could range from one or two stands in a management unit (e.g., a compartment) comprising less than 100 acres, a Ranger District, a National or State Forest, a county, state, or a forest region consisting of several states and millions of acres of forest. The overall size of the area will have a bearing on the survey methods selected and whether or not complete area coverage, sampling, or a multi-stage approach is the most logical approach.
Some general information requirements in forest health assessments that could be met by remote sensing include: 1) estimating area damaged or affected in relation to land ownership, topographic features, political boundaries and resource management objectives, and 2) intensity of damage across the affected areas or tree species affected by vegetation type, age, size or stocking classes. The nature of the signature (chapter 3) will have a bearing on whether or not remote sensing is a logical tool for data collection and the remote sensing tools needed to ensure that the information required is captured.

The accuracy of the data to be collected depends largely on how and when the data will be used. Some uses of the information collected by forest health protection specialists include:

- Taking action on the ground to improve forest health.
- Monitoring forest condition or the status and trends of pests and their damage over time.
- Seeking emergency funding for mitigation of catastrophic events that result in damage over extensive areas of forest.

In cases where the purpose of the assessment is to determine need for emergency funding following a catastrophic event, such as a hurricane or a widespread pest outbreak, information of the general location and intensity of damage in the affected areas, at least in the initial stages, may be sufficient. This information may have to be supplemented by more intensive surveys at a later date. If, on the other hand, the survey is intended to plan salvage operations or identify sites where direct suppression or other management actions are being considered, detailed information on the precise location of affected areas, the approximate number of damaged trees and their volume or the potential for damage in future years may be required. If the purpose of the information is to establish a baseline from which to monitor change over time, a reasonably high degree of both spatial and classification accuracy may be needed. In some instances, such as when estimates of resource damage is required, information on the level of statistical error may be an integral part of the information requirements.

The timeliness of the data is also a major consideration in planning a forest health assessment. A statistically sound dataset with a high level of confidence may be worthless if the data are not available when resource management decisions must be made. Survey design, data collection and analysis are time consuming processes, and must be balanced against the time that the data must be in the hands of a resource manager or decision-maker so that the potential appropriate actions can be evaluated, planned, and executed in a timely manner.

The format in which the data are to be presented is also a major consideration. In some instances, a map showing the location of a forest health problem may be sufficient. In other cases, it may be necessary to present an analysis of the data in a formal report. If major or potentially controversial actions to improve the health of forests on public lands are being considered, the data may have to be presented in a site-specific Environmental Analysis (EA) or Environmental Impact Statement (EIS) subject to public review and comment.

The most desirable approach to definition of the objectives and data requirements for a forest health assessment is to meet with the resource managers involved and reach a common agreement on what is needed and when it is needed. Unfortunately, this is not always possible because program
managers and/or decision-makers are often not available and many not have the technical skills required to make these decisions. Consequently they tend to rely on the technical specialists on their staffs—those who will ultimately collect the data—to make these determinations.

4.1.2. Biowindows

All surveys of forest damage, whether done by ground methods or remote sensing, must take place when the damaging agent is either in the proper stage of its life cycle, damage is at its peak, or in a stage where it can be most readily differentiated from previous year’s damage or from damage with a similar signature. The period during which these surveys should be conducted is called the survey biowindow.

Failure to identify the proper biowindow for a survey can result in serious overestimation or underestimation of damage. For example, fading caused by most western bark beetle species is visible throughout much of the year. However, it is during the summer months (June to August) when the difference in foliage color between the current year’s faders and previous years’ faders is most noticeable (chapter 3, Figure 3.10). Similarly, failure to consider optimum survey windows for defoliators of broadleaf forests could result in scheduling the survey too early, before larval feeding is completed, or too late, after some refoliation has already taken place, thus masking the damage. In either case, the area affected and intensity of damage could be underestimated.

Another factor that can influence the suitable time for mapping and assessment of forest damage is the occurrence of the spring flush of growth and fall coloring of deciduous trees and shrubs (aspens, oaks, maples, etc.). This can mask forest damage, which also appears as a change in the color of the forest canopy. The appearance of fall coloration of bald cypress (*Taxodium distichum*), a deciduous conifer indigenous to the southeastern United States is almost identical to the appearance of pines fading due to bark beetle attack (Billings and Ward 1984), and fall coloring of larches in northern forests can also be confused with tree fading caused by bark beetles.

4.1.3. Weather Considerations

The probability of suitable weather conditions for remote sensing occurring during the designated acquisition biowindow is another factor to be considered when planning a remote sensing mission. Virtually all remote sensing activities require good lighting and relatively cloud-free skies. Aerial sketchmap surveys can be flown under a wide range of weather conditions but are shut down by low cloud cover, rain and atmospheric turbulence. In areas of high humidity, such as the eastern U.S., low cumulus clouds often begin to appear as early as 9 to 10 A.M. These usually occur at altitudes of around 3,000 feet above ground level (AGL), below the flight altitude of most aerial photography missions using 9-inch mapping cameras. In addition to obscuring portions of the target area, cumulus clouds cause shadows on the ground, which can obscure additional area. A sky with 10 percent cumulus cloud cover could conceivably have another 10 percent of the ground surface obscured by cloud shadow. Most aerial photography missions can be flown under a partial cover of high cirrus clouds, but these will interfere with acquisition of imagery from high-altitude photography missions and Earth-orbiting satellites. Databases of archived satellite imagery usually provide an estimate of the amount of cloud cover on each scene. Cloud cover of less than 10 percent is generally considered acceptable imagery for most applications. However, since low clouds often
tend to lie over high-elevation areas (where forests also tend to occur), even this level of cloud cover may not be acceptable for forestry and forest health applications.

The probability of suitable weather conditions for acquisition of remote sensing data during a specified biowindow over any given target site is highly variable. California, at one extreme, tends to have cloud-free days during most of the summer. Other regions of the West also have a high probability of cloud-free conditions during the summer months. In the more humid eastern portions of North America, where low cumulus clouds are an artifact of even the best days, the probability of suitable weather for remote sensing activities is considerably lower. In some areas of the world, such as certain high-altitude tropical forests, the probability of cloud cover is so high as to preclude remote sensing as a viable means of data collection.

Data on the probability of days with greater than 10 percent cloud cover for any region of the U.S. during specified time periods is given by Lee and Johnson (1985) and can be used as a guide for planning remote sensing mission. A similar guide by Fleming (1970) gives patterns of suitable weather for aerial photography in Canada.

4.1.4. Classification Standards

Another important consideration in survey mission planning is how the data to be collected will be classified. Failure to define classification standards prior to the execution of a mission can result in inconsistencies in the resultant data, therefore reducing its quality and value. A common understanding of classification standards is especially critical if the assessment involves large areas of forest lands of different ownership and/or if a number of aerial observers, image interpreters or analysts, sometimes representing different organizations, are involved in the project.

Depending on the objectives of the survey, classification standards may have to be developed for certain vegetation types, tree species, or damage types based on the signatures described in chapter 3.

Classification standards can sometimes be presented in a simple narrative form that describe the characteristics of each class. For example, classification of forest defoliation may be defined as “aerially visible,” indicating the presence of areas of red-brown or gray-brown discoloration without regard to its intensity, or defoliation may be stratified into several classes such as “light,” “moderate,” or “heavy.” If several damage classes are to be recognized, they should be described so that all individuals involved in the survey have a common understanding of what constitutes each class. These descriptions can be accompanied by both aerial and ground photographs representative of each of the defined classes.

For more complex projects, as may be the case where several vegetation or damage types (e.g., tree mortality, dieback, or foliar discoloration) must be classified, or where there may be other signatures that could be confused with the signatures of interest, dichotomous keys accompanied by line drawings are often helpful—especially for image interpreters, who can take the time to make judgements on what they see on aerial photographs or digital images (Figures 4.1 and 4.2).
1. Forest area predominantly in dark red-brown or magenta hues (conifers)........ go to 2.
   1a. Forest area predominantly in red hues ............................................................... Broadleaves

2. Conifer stands below 3,000 feet........................................................................... Other species
   2a. Conifer stands above 3,000 feet................................................................. go to 3.

3. Stand boundaries irregular - generally conform to a topographic feature such as a
   drainage or ridge (natural forests).......................................................................... go to 4.
   3a. Stand boundaries more or less distinct, a sharp line of demarcation exists between
   conifer stands and adjoining hardwoods, often in distinct blocks and adjacent to
   roads (plantations)............................................................................................. go to 5.

   3a. Conifer component occupies greater than 50 percent of the canopy ..................
       ...................................................................................................................... Conifer (spruce or hemlock/spruce)
   4a. Conifer component occupies between 25 and 50 percent of the canopy ..........
       ...................................................................................................................... Mixed wood (spruce, hemlock hardwoods)

5. Trees occur in visibly distinct rows ..................................................................... Red pine
   5a. Trees not in visibly distinct rows ................................................................. Red or Norway spruce

Figure 4.1. Dichotomous key developed for identification of conifer stands with a red spruce
component on small-scale panoramic CIR aerial photographs on the Monongahela National Forest,
West Virginia (source: Mielke et al. 1986).

Figure 4.2. Vegetation types classified on a CIR aerial photography of a portion of the Monongahela
National Forest, West Virginia, with the aid of the key shown in Figure 4.1.
Murtha (1972a) presents a dichotomous key to photointerpretation of generic forest damage types. This key can be helpful in developing photointerpretation guides for more specific applications, to describe the sequence of injury symptoms over time (Lund et al. 1996, Murtha 1980), and to define how a normal, healthy tree should appear (Murtha and McLean 1981). Murtha (1983) describes the effect of photographic scale on classification of forest damage types.

General guidelines for recognition of specific damage types such as southern pine beetle infestations (Billings and Doggett 1980) or defoliation of broadleaf forests from low flying aircraft or on aerial photographs (Ward et al. 1986) have been developed and proven useful. More formal image interpretation guides, complete with data recording forms, have been developed in instances where a number of image interpreters are assembled and the data requirements are relatively complex (Ciesla 1984b).

4.1.5. Area Coverage

Forest Health assessments using remote sensing could involve complete coverage of the target area, sampling, or a combination of two in a multi-stage survey.

4.1.5.1. Complete Coverage - Complete area coverage is generally required if one of the data requirements is a map or maps showing the location of all damaged areas. This is a more or less standard practice during aerial sketchmap surveys (chapter 5) and is also a viable option in cases where high altitude, small-scale aerial photographs in the range of 1:24,000 to 1:30,000 will resolve the signatures of interest (chapter 6) or when using data acquired from Earth-orbiting satellites, which provide coverage of large areas of the Earth’s surface (chapter 9).

4.1.5.2. Sampling - Sampling is a process of using a portion of a population to describe the characteristics of the entire population. A sample is the part of a population used to obtain estimates of that population and sampling design or a sampling plan is a formalized process of selecting samples from a population (Schreuder et al. 1993).

There are many approaches to sampling, and volumes have been written about sampling and sampling designs. Two excellent references for forest sampling include a concise and comprehensive review by Freese (1962) and a more contemporary work by Schreuder et al. (1993).

Freese (1962) defines simple random sampling as a basic process that ensures that, when sampling a population of a given number of units, every possible combination of units has an equal chance of being selected. Stratified random sampling, on the other hand, is a method of drawing samples that takes advantage of information already known about the population. In stratified random sampling, the units of the population of interest are grouped together on the basis of some common characteristic. Each group or stratum is sampled, and group estimates are combined to give the population estimate. In forest health assessments, populations are often stratified according to some pre-determined level of damage intensity. Systematic sampling is a process in which samples are not drawn at random but according to some pre-specified pattern; usually the only element of randomization is in the selection of the starting point, and even that is often ignored. The most common pattern of systematic sampling consists of a grid having sampling units in equally spaced rows with a constant distance between units within rows. While statisticians tend to frown on
systematic sampling, most forest sampling is based on some form of this design. Reasons for favoring systematic sampling in forestry (and forest health assessments) are:

- The placement of sampling units is often easier and cheaper than random sampling.
- There is a perception that a sample deliberately spread over the entire population will be more representative than a random sample.

Sampling of forested areas is a common practice when using small or standard mapping format aerial photographs or airborne videographic imagery for forest health assessments. Under these conditions, the land area covered per scene is relatively small, and the costs, logistics, and time required for complete area coverage are prohibitive.

As is the case of sampling for other forestry applications (such as forest inventory), most sampling designs that call for remote sensing in forest health assessment have used a systematic sampling approach. Aerial photographic sampling usually consists of from two to five photographs taken in a strip with sufficient overlap from one photograph to the next to assure stereoscopic coverage over sample points on predetermined intervals along flight lines. Either an entire unit (e.g., a National Forest, county, state, etc.) may be covered in this manner, or a portion of the area within which areas of concentrated damage have been established by a previous survey (e.g., aerial sketchmapping: chapter 5, Figure 4.3). Navigational aids, such as GPS, are helpful when the precise location of photo-points is desired. Another approach is to not correct for air currents and drift during the aerial photography mission. This will introduce an element of randomness (quasi-random) into the distribution of photo-point samples over the survey area (Ciesla et al. 1967 and 1971b; Figure 4.4) and works well in areas where sufficient landmarks are present and can be positively identified on both the aerial photographs and the base maps to allow annotation of the location of each photo-point. Acquisition of complete coverage of small blocks of land (e.g., quarter sections of 7.5 minute USGS 1:24,000 scale map sheets), selected at random from the survey area, is another approach that has been used to sample large areas with aerial photographs for forest health assessments (Weiss et al. 1985b).

4.1.5.3. Multistage or Multiphase Sampling - Remote sensing is rarely used by itself as a means of data collection. Usually assessments involve a large remote sensing sample and a small ground sample to verify or correct estimates made from the aerial sample. Survey designs referred to as multistage or multiphase sampling have been both popular and effective approaches to acquiring data from a combination of remote sensing and ground sampling. In multistage sampling, the sampling units are selected in stages and samples at each stage are taken from the sampling units or clusters of units selected in the previous stage (Figure 4.5). Multiphase sampling is a variation in which the same size of sampling unit is used at each level of sampling but fewer units are selected at each succeeding phase (Schreuder et al. 1993).
Figure 4.3. Two sampling designs for using small or standard format aerial photography in forest health assessments. In A, aerial photo-plots are distributed on a systematic grid throughout the survey unit, resulting in estimates for the entire unit. In B, areas of damage have been stratified by aerial sketchmapping, and photo-plots are established on a systematic grid within these strata. Resultant estimates, therefore, are for the stratified areas only (redrawn from Ciesla 1984a).

Figure 4.4. Quasi-random distribution of aerial photo-points over a survey area. This pattern is the result of flying photo-points originally established on a systematic grid but no correction is made for drift during the photography mission (redrawn from Ciesla et al. 1971b).
Figure 4.5. Multistage sampling design developed for inventories of losses caused by the mountain pine beetle, *Dendroctonus ponderosae* (redrawn from White et al. 1983).

A technique known as **double-sampling with regression** has been used for forest damage inventories in the western United States (Wear et al. 1966) and is an example of multiphase sampling. This involves establishment of a large sample of aerial photo-plots of known size on which counts of the attribute of interest (e.g., fading trees) are made. A small sample of photo-plots is selected at random and visited on the ground, where counts of the same attribute are made. A regression of ground counts over photographic counts is computed from the small sample to correct the large sample. Another multi-stage design that has been developed for forest health applications involves a process for selecting units of successive sampling stages based on the frequency of the occurrence of the attribute of interest. This is known as **probability proportional to size** or **PPS** sampling. There are two variations: 1) probability proportional to size with replacement and 2) probability proportional to size without replacement. In the former, when a sample is drawn, it is returned to the pool of possible selections and could be selected again. In the latter, when a sample is drawn, it is not returned to the pool of possible selections and cannot be redrawn (Schreuder et al. 1993). Sample analytical procedures for both double-sampling with regression and PPS sampling using aerial sketchmapping, aerial photographs, and ground surveys are presented in chapter 6.
4.2. DATA COLLECTION

In remote sensing there are two basic approaches to data collection: 1) observation or image interpretation and 2) image processing. **Observation or image interpretation** involves examination of a scene or image with the human eye and interpreting what is seen. This process makes use of the knowledge and experience of the interpreters to make informed judgements about what they see. While observation or image interpretation makes use of the two most powerful remote sensing tools available; the human eye linked to the human brain, it is subjective and based on the interpreter’s experience and individual biases. Different levels of skill and experience among interpreters can also lead to inconsistencies in data collection. Another drawback of observation or image interpretation is that it can be a time-consuming, often repetitive, and tedious process.

**Image processing** makes use of computers to extract the required information from images or digital data. Many remote sensing data extraction functions are best done by computers, especially those involving large volumes of repetitive data. While computer assisted analysis tends to be consistent and objective, the resultant data are only as good as the analysis routines or algorithms used to extract the information.

4.2.1. Observation or Image Interpretation

In forest health protection, observation or image interpretation involves two basic processes: **classification** and **enumeration**. **Classification** is the categorizing of areas of land into certain predefined classes (see section 4.1.4) based on vegetation, level of damage, numbers of fading trees, etc. **Enumeration** involves making counts of certain objects of interest, such as fading trees or trees in different damage classes.

In aerial sketchmapping (Chapter 5) and aerial photography (Chapter 6), virtually all data are currently collected via observation and image interpretation. In aerial sketchmapping, aerial observers record what they see from low flying aircraft onto maps and interpret the information based on their knowledge of signatures and local conditions. Extraction of data from aerial photographs is also an interpretive process. Since the techniques of data collection vary significantly with the type of remote sensing tool used, specific procedures are presented in detail in the subsequent chapters.

4.2.2. Image Processing

Image processing is the manipulation of spatial data in digital format by computers and includes, but is not limited to, **image classification** and **image enhancement** operations. The purpose of image processing is to create an accurate and easily interpretable map for a specific application.

4.2.2.1. The Image Analyst  - Although many operations are performed by the computer, successful image processing relies heavily on the knowledge and skill of the image analyst. The image analyst is a specialist who must ensure that the strengths of the data are fully exploited so that the information requirements are met. The image analyst should also have a good understanding of the information to be mapped and the characteristics of the image (Lachowski et al. 1996).

Image analysts should understand:
• The statistical principles that form the basis of image classification techniques.
• The causes of variation in land cover, vegetation, and forest health conditions.
• The causes of spectral variation in the imagery.
• The need to link items of interest (e.g., vegetation, land cover, and damage) with the spectral variation in the imagery.

4.2.2.2. Image Preprocessing - Image preprocessing or enhancement is performed on raw digital data to increase both the accuracy and interpretability of the image prior to classification. Lachowski et al. (1996) and the USDA Forest Service (1998a) describe some typical image preprocessing operations.

• **Radiometric correction** is a process that corrects for variations in the image due to sensor anomalies or environmental conditions, such as haze. The end result is an image with spectral values that represent as closely as possible the true spectral reflectances of the imaged features. Radiometric correction is an optional operation, and its use depends on the image quality and/or the need to work with true reflectance values.

• **Geometric correction** reorients the image to compensate for the Earth’s rotation and for variation in the position and attitude of the sensor. This process may also include positioning or warping an image into a map projection system so that accurate measurements can be made. This is an important step if the resultant data are to be used in a GIS with other geo-referenced layers of information.

• **Terrain correction** adjusts the image for relief distortion with the help of digital elevation data, and is used when precise locations of areas of interest are required and the target area has elevational differences of greater than 500 feet.

• **Image enhancement** is a series of techniques sometimes used to improve the visual interpretability of the image. The objective of image enhancement is to enhance visual differences, thus making them more obvious to the interpreter. These techniques include principle component analysis or edge enhancements, which are performed on some or all spectral bands prior to classification. This is a particularly important step if the image is to be interpreted visually rather than by a computer.

• **Feature selection** is a means of reducing the volume of data in a digital image. Feature selection involves identification and isolation of individual raw spectral bands containing the most useful information for a particular application. All subsequent processing will be performed on only the selected spectral bands. In most cases, the most informative band combinations include at least one band from the visible, near-IR, and mid-IR regions of the EMS.

• **Data transformations** in the form of principal components or “tasseled cap” transformations can compress information and extract the most useful data for classifications.
4.2.2.3. **Image Classification** - Image classification is the process of assigning digital image data to various categories or classes on a pixel-by-pixel basis. A correctly classified image displays areas on the ground that share a particular feature of interest. There are two basic image classification techniques: **supervised** and **unsupervised**. A supervised classification depends on the direct involvement of the image analyst in the pattern recognition process. This technique requires the analyst to select training samples of known characteristics from the data that represent the patterns to be classified. Training samples or training sites are geographical areas of pixels that have been identified to contain characteristics of interest to the project via ground examination or aerial photographs and are used to “calibrate” the classification process. Unsupervised classification techniques are computer-automated methods of spectral pattern recognition, in which some parameters are specified by the user to uncover statistical patterns inherent in the data. Unsupervised classifications categorize discreet classes by grouping similar observations, and are useful for identifying training sites and image classification (Lachowski et al. 1996).

There are many approaches to computer-aided image classification. An overall approach that has worked well for a number of USDA Forest Service Applications involves a seven-step process (Lachowski et al. 1996, USDA Forest Service 1998a):

- **Step 1**: Divide the image into ecologically distinct areas to minimize confusing discrete land cover classes that appear spectrally similar on the image.

- **Step 2**: Identify training sites across each unit identified through prior knowledge of vegetation types on the ground.

- **Step 3**: Analyze training sites via field visits or aerial photographs. These will be used to establish the classification parameters.

- **Step 4**: Perform an unsupervised classification on each area to identify spectral variability. This is an automated process in which the computer separates spectral classes on the image. The image analyst specifies the number of parameters, including the desired number of spectral classes. The result of an unsupervised classification is a map in which each category represents a unique spectral class.

- **Step 5**: Analyze training sites and unsupervised spectral classes using evaluation techniques (for example, signature plots and divergence matrices) to develop an optimum set of signatures. One analytical method for accomplishing this task is known as a **cluster analysis**. This technique aids in labeling unsupervised classes by grouping them with supervised training sites, and also helps to identify limitations of the classification process.

- **Step 6**: Perform final image classification by combining the statistics from supervised and unsupervised classes.

- **Step 7**: Model/edit problem areas of the map to improve its accuracy. Some attributes that can be modeled include vegetation composition, size class, and crown closure.
The classified pixels resulting from this process can be combined into polygons with common attributes for entry into a GIS.

### 4.2.3. Change Detection

Change detection is a procedure that involves a systematic comparison of two or more images of the same part of the earth’s surface acquired at different times. Purpose of the comparison is to detect change. These analysis could address changes in land use patterns, distribution and abundance of certain vegetation types, or in vegetation condition.

In some instances, change detection has been done by visual interpretation of multi-temporal images. For example, a tropical forest resources assessment conducted by the Food and Agriculture Organization (FAO) of the United Nations (UN) involved comparison of pairs of Landsat images taken at about 10-year intervals to map changes in land cover. These data provided regional estimates of tropical deforestation rates and changes in biomass by forest region for the decade of the 1980s (FAO 1996). In most cases, however, analysis of change involves the systematic comparison of digital data by an image analyst working on a computer.

Many change detection analysis involve the computation of a vegetation index on a pixel-by-pixel basis for two or more multi-temporal images and comparing the resulting values. A vegetation index is usually a simple ratio or ratios of linear combinations of blue, green, red, or near-IR spectral reflectance values, and is used to make inferences about vegetation and its condition. A number of vegetation indices have been developed and are summarized by Murtha et al. (1997).

One of the most widely used vegetation indices is the normalized difference vegetation index (NDVI) (Pearson and Miller 1972). This is a relatively easy index to compute, and is based on visible red and near-IR reflectance values:

$$\text{NDVI} = \frac{\text{near-IR} - \text{red}}{\text{near-IR} + \text{red}}$$

NDVI values are in the range of -1 to +1, and are an indirect measure of photosynthetic activity of living plants or “greenness.” Negative values generally represent clouds, snow, water, dead trees, or other non-vegetated areas. The higher the NDVI, the more “green” the vegetation. The highest NDVI values that can be expected for green vegetation in North America are around 0.66. As herbaceous vegetation heals or trees die, the amount of red reflectance increases and NDVI decreases (Figure 4.6). Measurements of NDVI from composite images taken by the National Oceanic and Atmospheric Administration (NOAA) Advanced High-Resolution Radiometer (AVHRR) satellite (chapter 9) for two-week intervals show changes in vegetation condition due to curing of herbaceous vegetation and are helpful for assessment of fuel conditions and wildfire danger (Burgan and Hartford 1993).
Figure 4.6. The effect of increased red band reflectance on NDVI values (based on theoretical values generated by the author).

An interactive procedure has been developed by specialists of the USDA Forest Service Remote Sensing Applications Center (RSAC) that allows for comparison of three multi-temporal Landsat MSS images using NDVI. These datasets are useful for trend analysis, comparison of landscape changes on lands of different ownerships, and other vegetation change detection applications. For long-term change detection, it is important to compare images taken at roughly the same time of year so that seasonal changes in vegetation condition are not a source of error (USDA Forest Service 1998a).

4.2.4. Image Analysis Software

Image analysis software is an essential tool for computer assisted image analysis. A number of commercially produced software packages, with a wide range of applications, are currently available. Most are designed to be used on platforms such as Windows NT 4.0, Windows 95/98, and UNIX.

One of the more popular image analysis systems available is the ERDAS IMAGINE product suite. ERDAS, an Atlanta, Georgia-based software producer, pioneered in the development of the first PC-based image-processing software in 1978. This development was partially in response to work conducted by the USDA Forest Service, Southern Region, to evaluate Landat MSS data for assessment of forest damage. Present-day versions of ERDAS IMAGINE include add-on modules for a wide range of special applications, including a GIS interface, subpixel classifier, and a suite of photogrammetric products.
4.3. **ACCURACY ASSESSMENT**

Accuracy assessment is a process that determines how well the spatial and thematic classification of a product derived from remote sensing represents actual ground conditions. It is important to keep in mind that, in remote sensing, all of the data acquired are based on signatures. Failure to interpret or classify these signatures correctly will result in error. It is virtually impossible, even for the most skillful and experienced aerial observers or image interpreters, or for the best digital image-processing algorithms, to make correct classifications all of the time. Assessment of the accuracy of a survey gives both the specialists who acquired and analyzed the data and the ultimate user of the data an indication how closely the information derived from remote sensing actually agrees with conditions on the ground.

As a minimum, accuracy assessments should be conducted anytime a new remote sensing tool is evaluated, an existing remote sensing tool is used for a new application or if a new classification system has been developed and requires testing.

4.3.1. **Types of Errors in Remote Sensing**

Errors in remote sensing can be summarized statistically as omission and commission errors.

4.3.1.1. **Omission Error** - This is the error associated with failure to recognize or classify all of the objects of a specified category. For example, if there are 102 dying ponderosa pines in an area and the aerial observer or image analyst counts only 80, then 78 percent (80/120 • 100) of the trees were classified correctly but there was an omission error of 22 percent (100-78). Omission error is equivalent to the statistical error known as $\alpha$: the error associated with rejecting a hypothesis when it is true.

4.3.1.2. **Commission Error** - This is the error associated with classifying objects into a given category when they belong in another class. For example, if 100 dying trees were classified as ponderosa pines but ground verification established that two of these trees were actually dying cedars, then there was a commission error of 2.04 percent (100/98 • 100). Commission error is equivalent to the statistical error known as $\beta$: the error associated with accepting a hypothesis when it is false.

4.3.2. **The Error Matrix**

The primary statistical tool for accuracy assessment is the error or confusion matrix. An error matrix is a square array of numbers set out in rows and columns that express the number of sample units (pixels, clusters, polygons, etc.) assigned to a particular category in one classification relative to the number of sample units assigned to a particular category in another classification. In most cases, one set of classifications is considered to be correct or more correct and is known as the reference data (Congalton and Green 1999). The other set of classifications is done via remote sensing and there is a need to know its accuracy. The data in the error matrices shown in Tables 4.1 and 4.2 show the agreement between classification of forest defoliation by two independent aerial observers into three classes; None, Light to Moderate defoliation (L-M) and Heavy defoliation (H), compared with a reference dataset developed from aerial photointerpretation of the same site. The
cell values represent 100 sample points at which the classification of each aerial observer was compared with the reference data.

Once the data are arrayed in individual cells as displayed in Tables 4.1 and 4.2, some simple statistics can be computed about the error matrix. The percent correct classification or observed agreement is determined by adding the correct classifications in the diagonals and dividing by the cell total. For example in Table 4.1, observed agreement is:

\[
35 + 25 + 15 = 75/100 = 0.75, \text{ or 75 percent}
\]

Table 4.1. Error matrix of a hypothetical comparison between aerial sketchmapping by aerial observer 1 and aerial photographic reference data of forest defoliation.

<table>
<thead>
<tr>
<th>Aerial Photography Reference Data</th>
<th>Class</th>
<th>None</th>
<th>L-M</th>
<th>Heavy</th>
<th>Σ Rows</th>
<th>Commission Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerial Sketchmap Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>35</td>
<td>4</td>
<td>2</td>
<td>41</td>
<td>14.6</td>
</tr>
<tr>
<td></td>
<td>L-M</td>
<td>4</td>
<td>25</td>
<td>6</td>
<td>35</td>
<td>28.6</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>0</td>
<td>9</td>
<td>15</td>
<td>24</td>
<td>37.5</td>
</tr>
<tr>
<td></td>
<td>Σ Columns</td>
<td>39</td>
<td>38</td>
<td>23</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Omission Error (%)</td>
<td>10.3</td>
<td>34.2</td>
<td>34.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( Σ \) main diagonal = 75
Observed agreement (percent) = 75
Chance agreement (percent) = 34.8
Kappa (\( κ \))* = 0.617
Variance \( κ \) = 0.004246
95 percent confidence limits (\( κ \)) = 0.608 - 0.625
\( Z (κ) \) = 9.46**

* See subsection 4.3.3 for an explanation of Kappa.
** \( Z(κ) \) greater than 1.96 indicates agreement is significantly better than chance agreement at 95 percent confidence level.
Table 4.2. Error matrix of a hypothetical comparison between aerial sketchmapping by aerial observer 2 and aerial photographic reference data of forest defoliation.

<table>
<thead>
<tr>
<th>Aerial Sketchmap Data</th>
<th>Class</th>
<th>Non</th>
<th>L-M</th>
<th>Heavy</th>
<th>Σ Rows</th>
<th>Commission Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerial Photography Reference Data</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Class</td>
<td>Non</td>
<td>L-M</td>
<td>Heavy</td>
<td>Σ Rows</td>
<td>Commission Error (%)</td>
</tr>
<tr>
<td></td>
<td>None</td>
<td>32</td>
<td>8</td>
<td>4</td>
<td>44</td>
<td>27.3</td>
</tr>
<tr>
<td></td>
<td>L-M</td>
<td>5</td>
<td>20</td>
<td>8</td>
<td>33</td>
<td>39.4</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>0</td>
<td>10</td>
<td>13</td>
<td>23</td>
<td>43.5</td>
</tr>
<tr>
<td></td>
<td>Σ Columns</td>
<td>37</td>
<td>38</td>
<td>25</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Omission Error (%)</td>
<td>13.5</td>
<td>47.4</td>
<td>48.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Σ main diagonal = 65
Observed agreement (percent) = 65
Chance agreement (percent) = 0.346
Kappa (κ)* = 0.465
Variance κ = 0.005064
95 percent confidence limits (κ) = 0.455 - 0.475
Z (κ) = 6.54**

* See subsection 4.3.3 for an explanation of Kappa.
** Z(κ) greater than 1.96 indicates agreement is significantly better than chance agreement at 95 percent confidence level.

Omission and commission error can be determined for each class in the error matrix (Lo and Watson 1998). Omission error is measured adding the non-diagonal cell values (those that indicate no agreement) in each column and dividing the sum by the column total. In the error matrix shown in table 4.1 omission error for the L-M class is determined as follows:

\[ \frac{4+9}{38} = 0.342, \text{ or } 34.2 \text{ percent} \]

Commission error is measured by adding the non-diagonal cell values (those that indicate no agreement) in each row and dividing the sum by the row total. Again, for the error matrix in table 4.1, commission error for the L-M class is:

\[ \frac{4+6}{35} = 0.286, \text{ or } 28.6 \text{ percent} \]
In certain applications, such as determining map accuracies, omission error and commission error are expressed, respectively, as **producer’s accuracy** and **user’s accuracy** (Congalton and Green 1998). These are determined by dividing the value for each class in the diagonal (agreement value) by the column or row total. This results in a number that is the reciprocal of the omission or commission error. For example, using the data from Table 4.1, producer’s accuracy for the L-M class is:

\[
\frac{25}{38} = 0.658, \text{ or } 65.8 \text{ percent}
\]

User’s accuracy is:

\[
\frac{25}{35} = 0.714, \text{ or } 71.4 \text{ percent}
\]

### 4.3.3. The Kappa Statistic

The computation of overall or observed agreement includes an element of **chance agreement**. This is the agreement that would occur if someone simply made a random guess at classifying the data. An example of chance agreement is the agreement one would expect to achieve when taking a multiple choice test and simply guessing at the answers. For example, if one were to guess at the answer to a multiple choice question given five choices, the chance of making a correct guess is one out of five, or 20 percent. Computation of a statistic known as **Kappa**, Khat, or κ, accounts for chance agreement in the error matrix. κ is a **measure of agreement** based on the difference between the observed agreement in the error matrix and the chance agreement as indicated by the row and column totals of the error matrix (Cohen 1960) and is computed as follows:

\[
\kappa = \frac{\text{observed agreement} - \text{chance agreement}}{1 - \text{chance agreement}}
\]

Chance agreement for each cell is the product of the column and row totals divided by the total number of observations in the error matrix, and chance agreement for the error matrix is the sum of the chance agreement values in the diagonal. Individual diagonal cell chance agreement for the error matrix in Table 4.1 is:

\[
\begin{align*}
39 \times 41 &= 1599/100 = 16.0 \text{ percent} \\
38 \times 35 &= 1330/100 = 13.3 \text{ percent} \\
23 \times 24 &= 552/100 = 5.5 \text{ percent}
\end{align*}
\]

Chance agreement for this error matrix is:

\[
16.0 + 13.3 + 5.5 = 34.8 \text{ percent}
\]

Kappa or κ for this error matrix is:

\[
(0.75 - 0.348)/(1 - 0.348) = 0.617
\]
The values of $\kappa$ can range between +1 and -1. Since there is, at least theoretically, a positive correlation between remote sensing and reference data, positive values of $\kappa$ are expected. An interpretation of the values of $\kappa$ is given by Landis and Koch (1977) as follows:

<table>
<thead>
<tr>
<th>Interpretation</th>
<th>$\kappa$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong agreement</td>
<td>$\kappa &gt; 0.80$</td>
</tr>
<tr>
<td>Moderate Agreement</td>
<td>$0.40 \leq \kappa \leq 0.80$</td>
</tr>
<tr>
<td>Poor Agreement</td>
<td>$\kappa &lt; 0.40$</td>
</tr>
</tbody>
</table>

4.3.4. The Kappa Analysis

The kappa or $\kappa$ analysis is a discreet multivariate technique used for determining if one error matrix is statistically different from another (Bishop et al. 1975). This analysis is based on the computation of a combined $z$-value for the two error matrices. If $z$ exceeds 1.96, then the two error matrices are significantly different at the 95 percent confidence level. This technique has been widely used in sociology and psychology, and was introduced for analysis of remote sensing data (e.g., a classification by remote sensing versus classification by some form of reference data) by Congalton (1981). Today, $\kappa$, or KHAT analysis is a standard component of many accuracy assessment analysis in remote sensing.

Computation of the variance of $\kappa$ is complex and determined as follows:

$$\varsigma^2 \kappa = \frac{1}{N} \cdot \left( (((\theta_1)(1-\theta_1)/(1-\theta_1)^2) + ((2)(1-\theta_1)(2\theta_1\theta_2 - \theta_3))/(1-\theta_2)^3 + ((1-\theta_1)^2 (\theta_4 - 4\theta_2)^2)/(1-\theta_2)) \right)^4$$

and:

$$\theta_1 = \sum (x_{ii}/N)$$

$$\theta_3 = \sum (x_{ii}/N)(x_{i+}/N + x_{+i}/N)$$

$$\theta_2 = \sum (x_{i+} \cdot x_{+i})/N^2$$

$$\theta_4 = \sum (x_{ii}/N)(x_{i+}/N + x_{+i}/N)^2$$

Once the variance of $\kappa$ is known, an error matrix $z$ value can be computed to determine if observed agreement is significantly better than chance agreement as follows:

$$z(\kappa) = \kappa / \sqrt{\text{variance}(\kappa)}$$

where $z(\kappa) \geq 1.96$ indicates that agreement is significantly better than chance agreement 95 out of 100 times.

The test statistic to determine if two independent error matrices and their $\kappa$ values are significantly different is:

$$z = \kappa_1 - \kappa_2 / \sqrt{\text{var} \kappa_1 + \text{var} \kappa_2}$$

When $z(\kappa_1 - \kappa_2)$ is greater than or equal to 1.96, it indicates that agreement is significantly better than chance agreement 95 out of 100 times.
For the data presented in tables 4.1 and 4.2, the respective values of $\kappa$ and its variance are as follows:

<table>
<thead>
<tr>
<th></th>
<th>$\kappa$</th>
<th>$\xi^2 \kappa$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error matrix 1 (table 4.1) -</td>
<td>0.617</td>
<td>0.004246</td>
</tr>
<tr>
<td>Error matrix 2 (table 4.2) -</td>
<td>0.465</td>
<td>0.005064</td>
</tr>
</tbody>
</table>

and:

$$z = \frac{0.617 - 0.465}{\sqrt{(0.004246 + 0.005064)}}$$

$$z = 1.575$$

Since $z$ is less than 1.96, there is no significant difference between these two error matrices at the 95 percent confidence level indicating that the classifications by the two aerial observers are not different.
5. AERIAL SKETCHMAPPING

Aerial sketchmapping is the oldest and most widely used remote sensing tool in forest health protection. This chapter describes the strengths and weaknesses of aerial sketchmapping, uses of the resulting data, personnel and equipment needs, planning and conduct of aerial sketchmap surveys, safety protocols, and quality standards.

5.1. OVERVIEW

Aerial sketchmapping is a relatively simple and low cost method of monitoring forest condition. Trained observers, working in low-flying aircraft generally at a flying height of between 1,000 - 2,500 feet AGL and at an airspeed of about 90-125 mph, locate damaged areas and “sketch” those locations onto maps as coded points or polygons according to pre-determined classification schemes.

Sketchmapping is used primarily for mapping tree mortality caused by coniferous bark beetles and foliar injury due to defoliating insects. In many forest regions of the United States, these two groups of insects contain pests of major economic importance, capable of causing widespread damage. Examples include the southern pine beetle in the Southeast; mountain pine beetle (*D. ponderosae*), Douglas-fir beetle, and fir engraver in the West; defoliators such as eastern spruce budworm (*Choristoneura fumiferana*) in Maine and the Great Lakes Region; western spruce budworm in the West; and the introduced gypsy moth in the East. Sketchmapping has also been used to map damage caused by certain tree killing pathogens and climatic events such as hurricanes and ice storms.

Guidelines describing techniques and protocols for aerial sketchmapping of forest damage have been published for several forest regions of the United States (USDA Forest Service 1970, Wear and Buckhorn 1955), for the entire United States (Klein et al. 1983, McConnell et al. 2000), and specifically for southern pine beetle (Billings and Doggett 1980, Billings and Ward 1984).

5.2. HISTORICAL PERSPECTIVE

Small aircraft have been used for many years in detection and assessment of forest damage. In 1919, Hewitt (1919) reported using aircraft to survey mosquito breeding areas in portions of British Columbia, Canada, and recommended its use in detection of forest insect damage. In 1920, an open-cockpit aircraft equipped with pontoons was used to map an infestation of spruce budworm in portions of Quebec and Ontario, Canada (Swaine 1921). Aerial observations on bark beetle caused damage was made from a DH-4 bi-wing aircraft in California as early as 1927 (Furniss and Wickman 1998). At the end of World War II, when there was an increased number of military trained pilots and civilian-class aircraft available, aerial sketchmapping became a routine method of data collection. In the Pacific Northwest, for example, a cooperative state-U.S. Forest Service forest insect detection survey has been conducted annually since 1947 (Johnson 1995). Research designed to develop mapping standards and observation limits for aerial sketchmapping was conducted by USDA Forest Service units based in Beltsville, MD and Portland, OR (Aldrich et al. 1958, Heller et al. 1955).

A variation of aerial sketchmapping, known as the Operation Recorder survey, was first tested in Maine in 1950 for estimating area defoliated by spruce budworm (Heller et al. 1952). This involved
an aerial observer viewing the forest through a strip viewer attached to the window of the aircraft and classifying damage on a sample strip of known width. Data, including severity of defoliation or occurrence of bark beetle spots, were recorded via a keyboard to a 20-pen operations recorder. This survey method was widely used over portions of the southeastern United States for bark beetle surveys (Ketcham 1964) but was eventually replaced by aerial photography (USDA Forest Service n.d.).

5.3. **STRENGTHS AND WEAKNESSES**

The strength of aerial sketchmapping is that it is a cost-effective means of covering large areas of remote, inaccessible forests rapidly. An experienced aerial survey team can cover up to 750,000 acres in a day. In the Pacific Northwest (Oregon and Washington) in 1995, two teams of two aerial observers each, one representing USDA Forest Service and the other representing the respective state forestry agency, covered the region’s 54 million acres of forests in about six weeks at a cost of $70,000, or about $0.0013 per acre (McConnell 1995b).

The weakness of aerial sketchmapping is that data obtained from aerial sketchmapping are subjective and not repeatable. Aerial observers must know their exact location at all times, and even a moment’s confusion can result in the plotting of an area of damage in the wrong location. The quality of aerial sketchmap data, therefore, depends on the skill and experience of aerial observers and their familiarity with local forest conditions. Weather conditions affecting visibility and air turbulence also influence the quality of aerial sketchmap data.
5.4. USES OF AERIAL SKETCHMAP DATA

The term “aerial sketchmapping” has been used more or less synonymously with detection. In many parts of the United States, aerial sketchmap surveys are referred to as aerial detection surveys (Billings and Ward 1984). Detection, however, refers to discovery. While aerial sketchmapping is the primary tool for detection of forest damage in the most remote of forest regions (such as most of Alaska), in most areas forest damage is rarely “discovered” via aerial sketchmapping. Usually there is some prior knowledge of the existence of a problem, either from field reports or data from previous aerial sketchmap surveys. In addition, aerial sketchmap surveys provide forest health protection specialists and land managers with considerably more information than simply the presence or absence of a problem (Klein et al. 1983).

5.4.1. Current Status of Major Pests

The most important use of aerial sketchmapping is to acquire data on the location, intensity, and area affected by forest pests, especially tree killing bark beetles and defoliating insects. These data are summarized on maps and/or data tables by pest, area affected, intensity of damage, number of trees killed, and/or land ownership classes. Maps and summary data are provided to land managers in as short a time as possible to facilitate planning and conduct of salvage operations, suppression, or other actions as may be needed to help reduce pest losses. Aerial sketchmap surveys also provide data for reports of statewide, regional, and national forest pest conditions.

5.4.2. Historical Records of Pest Occurrence

A consistent series of aerial surveys, conducted over a long period, can provide a historic record of pest occurrence. These records can provide information on pest cycles, host and habitat preferences, and outbreak duration. For introduced insects, such as gypsy moth, historical records of defoliation can be used to help document the insect’s spread and to identify areas with a high potential for becoming infested. In some parts of the United States, the results of aerial sketchmap surveys conducted over many years have provided the basis for cartographic histories showing the location of areas affected by certain pest species, such as western spruce budworm (Dolph 1980) or Douglas-fir tussock moth (Tunnock et al. 1985). Historical data on pest occurrence are also being stored in GIS (Johnson 1995).

5.4.3. Planning and Evaluation of Suppression Projects

Aerial sketchmap data has been used to designate boundaries of areas to be treated with chemical or biological insecticides. In some instances, the effectiveness of insecticides in protecting foliage has been assessed from sketchmap surveys. For example, the effect of aerial applications of the bacterial insecticide, *Bacillus thuringiensis*, on subsequent defoliation by western spruce budworm in Oregon and Washington between 1982 and 1992 was evaluated by using aerial sketchmap surveys and a GIS. This evaluation indicated that the treatments reduced the extent of subsequent defoliation for about one year following treatment (Sheehan 1996).
5.5. SKILLS AND QUALIFICATIONS OF AERIAL OBSERVERS

Aerial observers are the key to successful aerial sketchmap surveys. The attributes of a successful aerial observer (Klein et al. 1983) include:

- Ability to identify major forest types and tree species in their area of responsibility (chapter 3, section 3.2).

- A working knowledge of the major damaging agents that occur in the observer’s area of responsibility, their biology, and characteristic damage signatures (chapter 3, section 3.3).

- A desire to fly and not be subject to vertigo or motion sickness.

- Good eyesight and color perception. Approximately 8.5 percent of men and 0.5 percent of women have red-green color perception problem, so aerial observers should be given a color perception test prior to receiving aerial sketchmap training (Figure 5.1).

- Ability to read maps and orient between the air and the ground.

Figure 5.1. A page from a color perception chart designed to test for red-green deficiency.

Experience has shown that about 100 hours of in-flight experience are required before observers become proficient aerial sketchmappers (Klein et al. 1983).

Pilots used for aerial sketchmap surveys should be experienced in flying small aircraft over extensive areas of rugged, remote terrain. They should also be familiar with the data collection procedures and safety protocols, and be an integral member of the aerial survey team.
5.6. **EQUIPMENT**

The essential equipment required for aerial sketchmapping are (Klein et al. 1983):

- A suitable aircraft.
- Maps or aerial photos for recording data.
- Pencils for data recording.
- Air sickness medication and containers.
- Safety equipment (see section 5.8)

Optional items of equipment include:

- Map boards or rollers.
- A 35 mm camera and color film.
- A small tape recorder.
- Emergency supplies and clothing (see section 5.8).

5.6.1. **Aircraft**

5.6.1.1. – Fixed-Wing Aircraft. High-wing, single-engine, fixed-wing aircraft have been the most widely used aircraft for aerial sketchmapping. These provide the ideal combination of visibility, maneuverability, ability to fly at relatively slow speeds (90-125 mph), and low cost. Four- and six-place aircraft are preferred to two-place aircraft because they can accommodate more aerial observers, maps, and other equipment needed for the surveys.

Aircraft performance is important, especially in the high, mountainous regions of the West. In the eastern United States and Canada, survey altitudes typically range between 500 and 4,000 feet above MSL. However, in the West, the flying heights of survey aircraft may range between 4,000-9,000 feet above MSL, and occasionally, as high as 11,000 feet. During the summer months, when temperatures are higher, consideration of flight altitude is critical because of density altitude. This is an expression of the air density through which the aircraft flies and is dependent on temperature, relative humidity and altitude. For example, an airstrip may be at an elevation of 3,000 feet above MSL, but on a given day, its density altitude may be computed at 6,000 feet. This means that the aircraft can be expected to perform at 3,000 feet MSL as it would normally be expected to perform at 6,000 feet MSL (Klein et al. 1983).

Minimum power requirements for single-engine four-place aircraft that fly under 5,000 feet MSL is 150 horsepower (HP). For aircraft flying above 5,000 feet, the minimum requirement is 225 HP. In portions of the Rocky Mountains and Great Basin areas, where survey altitudes above 7,000 feet are not uncommon, turbo-charged aircraft have been used to provide added performance and safety. A summary of the high-wing single engine aircraft manufactured by the Cessna Aircraft Corporation is given in Table 5.1, and some aircraft available for aerial sketchmapping are shown in Figure 5.2. With the exception of the Cessna 177RG and 210, which have retractable landing gear, all of the other aircraft listed in Table 5.1 can be fitted with floats for water take-offs and landings. Other single-engine, high-wing aircraft that have been used for aerial sketchmapping include the Piper Tri-Pacer (low elevations only) and the DeHavilland Beaver.
In some of the more mountainous areas, twin-engine aircraft have been used with varying degrees of success. Examples include the Cessna 337 Skymaster, the Aero Commander 500 series, and the Partnavia P 68 series (see Figure 5.2). Twin engines provide an added margin of safety, but the aircraft are also heavier, and must be flown at higher airspeeds to maintain air-worthiness. Because of its protruding engine cowl, the Cessna Skymaster has only fair forward visibility but excellent downward lateral visibility. A pressurized version of the Cessna Skymaster has smaller windows, which restrict visibility. The Aero Commander 500 series aircraft have excellent visibility from the front seats but poor visibility from the back seats. The Partnavia P-68 series are excellent aerial sketchmap aircraft, especially the model P-68 Observer, which can be equipped with a bubble front window. A number of aircraft suitable for aerial sketchmapping can be modified with a short takeoff and landing (STOL) conversion, which permits slower flying speeds and short airstrip operation. This conversion adds to the cost of the aircraft, however, and to operating costs.

Table 5.1. Characteristics of some Cessna high-wing single-engine aircraft

<table>
<thead>
<tr>
<th>Aircraft Model</th>
<th>Engine HP</th>
<th>Number of Seats</th>
<th>Other Characteristics</th>
<th>Suitable for Aerial Sketchmapping?</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>100</td>
<td>2</td>
<td>Used primarily for flight training</td>
<td>No</td>
</tr>
<tr>
<td>172 (Skyhawk)</td>
<td>150</td>
<td>4</td>
<td>Low-elevation areas only</td>
<td></td>
</tr>
<tr>
<td>177 (Cardinal)</td>
<td>180</td>
<td>4</td>
<td>Low-elevation areas only</td>
<td></td>
</tr>
<tr>
<td>177RG</td>
<td>180</td>
<td>4</td>
<td>Retractable landing gear</td>
<td>Low-elevation areas only</td>
</tr>
<tr>
<td>180</td>
<td>230</td>
<td>4</td>
<td>Bicycle landing gear</td>
<td>Yes</td>
</tr>
<tr>
<td>182 (Skylane)</td>
<td>230</td>
<td>4</td>
<td>Tricycle landing gear</td>
<td>Yes</td>
</tr>
<tr>
<td>185</td>
<td>285-310</td>
<td>4</td>
<td>Bicycle landing gear</td>
<td>Yes</td>
</tr>
<tr>
<td>206</td>
<td>285</td>
<td>6</td>
<td>Tricycle landing gear</td>
<td>Yes</td>
</tr>
<tr>
<td>207</td>
<td>285</td>
<td>7</td>
<td>Tricycle landing gear</td>
<td>Yes</td>
</tr>
<tr>
<td>210</td>
<td>285-310</td>
<td>6</td>
<td>Tricycle landing gear</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Retractable landing gear
Figure 5.2. Examples of aircraft used in aerial sketchmapping. **Upper left:** Cessna 172. **Upper right:** Cessna 182. **Middle left:** DeHaviland Beaver equipped with floats. **Middle right:** Cessna 337 Skymaster. **Lower left:** Aero Commander 500B. **Lower right:** Partenavia P-68.

5.6.1.2. – **Helicopters.** Helicopters are an excellent aerial survey aircraft because they can fly at slower speeds, at lower altitudes, and are more maneuverable than fixed-wing aircraft. However, they are considerably more expensive to operate. Helicopters have been used for intensive surveys such as mapping concentrated windthrow and salvage opportunities (Klein et al. 1983) and for detecting root disease centers (Valcarce 1964). The Bell B-1 helicopters have excellent visibility but can only accommodate a pilot and one observer. The Bell 206 Jet Ranger has excellent front-seat visibility but rear-seat visibility is limited.
5.6.2. Maps
Maps of good quality are essential to an aerial sketchmap survey. They should be the most recent edition available so that new construction, changes in river channels, and other new features appear on the maps. They must also be of the appropriate scale to meet the survey objectives. Large-scale maps will permit more accurate positioning of forest damage but will be flown over more quickly, and more maps must be carried in the limited space available in a survey aircraft. Figure 5.3 illustrates some of the different maps available for use in sketchmapping.

Experience has shown that maps of scales ranging from 1:50,000 to 1:125,000 are adequate for general purpose aerial sketchmapping. Topographic maps, if available, are preferable to planimetric maps although both have been used. The USDA Forest Service or Bureau of Land Management (BLM) planimetric maps of a scale of 1:126,720 (½ inch = 1 mile) have been widely used for aerial sketchmap surveys, especially in the western U.S. where there are extensive, contiguous areas of public forest lands. These maps are relatively accurate, show a moderate level of detail and usually display major land ownership classes (e.g., National Forest, BLM, National Park, State, etc), a feature helpful for summarizing location of forest damage by land ownership class (Figure 5.3A.).

The new 1:100,000 scale USGS metric topographic map series has recently become a popular map base for aerial sketchmapping (Figure 5.3B, McConnell 1995b). The 7.5 minute, 1:24,000 scale USGS topographic maps or orthophotos (Figure 5.3C) are an excellent base for intensive mapping of small, localized areas of damage, especially from a helicopter. These maps are too large a scale for general purpose aerial sketchmapping over large areas of forest, however, because too many maps are required for a mission and it is awkward and time consuming for aerial observers to change maps every few minutes. The 15 minute USGS 1:62,500 topographic maps were an excellent map base for sketchmapping but have been discontinued. Black and white aerial photo mosaics at scales of 1:20,000 have also been used as a map base for aerial sketchmapping (Heller et al. 1955). More recently, Landsat images, printed and enlarged to a desired scale have been used for aerial navigation. These images lack some necessary detail but do show forested areas and recent land form changes (Klein et al. 1983). In Minnesota, the state’s Department of Natural Resources has developed 1:100,000 scale CIR vegetation maps based on Landsat data overlain with USGS thematic data. These are widely used for aerial sketchmapping (Figure 5.3D).

5.6.3. Other Equipment
In addition to a suitable aircraft and maps of good quality for recording locations and intensities of forest damage, other equipment needs fall into the “optional” category and include:

- Map board or map roller
- Small-format camera
- Portable tape recorder
- Special lenses or filters for viewing forest damage
Figure 5.3. Examples of map used for aerial sketchmapping: A. USDA Forest Service planimetric forest map (scale = 126,720), B. USGS 1:100,000 metric topographic map, C. USGS 1:24,000-7.5 minute topographic map and D. Landsat derived vegetation map with USGS 1:100,000 scale thematic overlays produced by the Minnesota Department of Natural Resources.

Map boards are simply a piece of Masonite, plywood, or other stiff material, approximately 11 x 14 inches in size. The map board is held in the aerial observer’s lap and used as a portable table on
which to place the survey map during sketchmapping. An alternative device is the map roller, a means of holding and viewing an assembled, continuous map for a survey area. To use a map roller, survey maps are first cut into strips of an appropriate size, glued end-to-end, and wound onto a wooden spool. The filled spool and an empty spool are inserted into the map roller, and the aerial observer winds the roller’s knobs to pull the map strip from one spool to the other across a flat surface. The sketchmapper plots forest damage information on the strip segment on the flat surface of the map roller table (Billings and Ward 1984).

**Small format cameras** are valuable for recording examples of forest damage encountered during sketchmap surveys. Oblique photos, taken through the window of the aircraft, are helpful in briefing forest managers on the status of damaging agents, for making counts of dying trees in areas of heavy damage, and for training new aerial observers. Standard 35-mm cameras, loaded with a color film with an ASA or ISO film speed of 100 or higher, are most widely used. In recent years, digital cameras have also become popular for recording damage, especially the Kodak DCS 420 digital CIR camera (see chapter 7, section 7.2.1), which produces images that simulate CIR film (see chapter 6, section 6.6.3). Camera shutter speeds should be set at 1/250 of a second or higher to minimize image motion. Aerial observers should avoid using telephoto lenses on single-lens reflex cameras because the magnification effect will sometimes increase the risk of motion sickness. Moreover, they are more likely to produce photos with image motion.

A small, portable, battery-operated **tape recorder** is helpful for recording information about areas that should be ground checked, specific locations of damaged areas and other pertinent information during aerial sketchmap surveys.

A variety of **sunglasses** with special filters have been evaluated for their ability to enhance certain colors and increase the ability to see forest damage. Billings and Ward (1984), for example, recommend sunglasses with a yellow filter. Sunglasses equipped with Cosmetan smoky amber lenses tend to make red hues stand out more clearly, and were once thought to be beneficial for aerial surveys of southern pine beetle. But these lenses had a tendency to make all reds seem brighter, including the red-brown crown color typically associated with spots that were no longer active, and caused aerial observers to record superfluous information.
5.7. PLANNING AND EXECUTING AERIAL SKETCHMAP SURVEYS

The success of an aerial sketchmap mission depends largely on a clear definition of the objectives of the survey and the quality of the planning. Mission objectives should be clearly defined and planning should begin well in advance of flights. Data from previous years surveys should be reviewed and priority areas should be designated. Inquiries should also be made to field units as to suspected problem areas. Field units should also be notified when survey flights are scheduled (Klein et al. 1983).

5.7.1. Observation Limits

An important factor to consider in aerial survey planning is what type of damage is visible from low flying aircraft and how well can it be seen. Years of aerial survey experience has shown, for example, that the detection threshold for insect caused defoliation in forests is removal of about 25-30 percent of the foliage. Therefore, supplemental ground surveys are required if it is necessary to detect areas of very light foliar injury. A study of observation limits for aerial sketchmapping trees killed by southern pine beetle in the southern Appalachian Mountains showed that ability to detect groups of dead trees (spots) varied by the size of the spot and the width of the flight strip observed (Aldrich et al. 1958; Table 5.2).

Table 5.2. Observation limits for aerial sketchmapping southern pine beetle infestations in the Southern Appalachian Mountains based on width of flight strip and spot size (data derived from Aldrich et al. 1958, page 202, Figure 3)

<table>
<thead>
<tr>
<th>Spot Size (number of faders)</th>
<th>Percent of spots detected by width of flight strip observed (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>1 tree</td>
<td>45</td>
</tr>
<tr>
<td>2-5 trees</td>
<td>58</td>
</tr>
<tr>
<td>6-20 trees</td>
<td>72</td>
</tr>
<tr>
<td>21-50 trees</td>
<td>85</td>
</tr>
<tr>
<td>51+ trees</td>
<td>100</td>
</tr>
</tbody>
</table>

5.7.2. Biowindows

The importance of recognizing survey biowindows for planning all assessment activities relevant to forest health protection has already been discussed in chapter 4, section 4.2. Ideally, when planning aerial sketchmap surveys, biowindows should be defined for each major damaging agent. However, because there are often a number of damaging agents present to be mapped, this is often not practical. Fortunately, the life cycles of many forest pests overlap to some degree, making it possible to survey for many species of bark beetles and defoliators simultaneously. This is especially true in western North America where most damage begins to appear by late June or early July and remains visible through September or even as late as mid-October (Klein et al. 1983) (Table 5.3). In northern Idaho and western Montana the annual aerial detection survey is made during July.
and August. The first areas flown are those where defoliator outbreaks are not anticipated because defoliation signatures are usually not visible before late July (McConnell 1995b).

Table 5.3. Optimum biowindows for aerial sketchmapping various North American forest insects (redrafted from Klein et al. 1983).1

<table>
<thead>
<tr>
<th>Forest Region</th>
<th>Insect</th>
<th>Host</th>
<th>Approx. Biowindow</th>
</tr>
</thead>
<tbody>
<tr>
<td>West</td>
<td>Mountain pine beetle</td>
<td>Pines</td>
<td>June 15 - September 30</td>
</tr>
<tr>
<td></td>
<td>Western pine beetle2</td>
<td>Ponderosa pine</td>
<td>June 1 - October 31</td>
</tr>
<tr>
<td></td>
<td>Ips engraver beetles3</td>
<td>Pines</td>
<td>May 1 - October 31</td>
</tr>
<tr>
<td></td>
<td>Douglas-fir beetle4</td>
<td>Douglas-fir</td>
<td>Mid May - October 31</td>
</tr>
<tr>
<td>Spruce beetle</td>
<td></td>
<td>Spruces</td>
<td></td>
</tr>
<tr>
<td>Western spruce budworm</td>
<td></td>
<td>True firs, Douglas-fir, spruce,</td>
<td>July 1 - October 15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>larch</td>
<td>July 1 - August 31</td>
</tr>
<tr>
<td>Douglas-fir tussock moth</td>
<td>Douglas-fir, true firs</td>
<td>Hemlock, Douglas-fir, true firs,</td>
<td>July 1 - August 31</td>
</tr>
<tr>
<td></td>
<td></td>
<td>spruce, true firs</td>
<td></td>
</tr>
<tr>
<td>Hemlock looper</td>
<td>Hemlock, Douglas-fir, true firs, spruce</td>
<td></td>
<td>August 1 - September 30</td>
</tr>
<tr>
<td></td>
<td>Lodgepole pine needle miner</td>
<td>Lodgepole pine</td>
<td>July 1 - August 31</td>
</tr>
<tr>
<td></td>
<td>Larch casebearer</td>
<td></td>
<td>May 15 - June 30</td>
</tr>
<tr>
<td>Northeast, Central and Lake States</td>
<td>Spruce budworm</td>
<td>Balsam fir, spruce</td>
<td>July 1 - 31</td>
</tr>
<tr>
<td></td>
<td>Gypsy moth</td>
<td>Various broadleaf trees</td>
<td>June 20 - July 20</td>
</tr>
<tr>
<td></td>
<td>Forest tent caterpillar</td>
<td>Aspen, oaks</td>
<td>June 5 - 30</td>
</tr>
<tr>
<td></td>
<td>Fall cankerworm</td>
<td>Various broadleaf trees</td>
<td>June 5 - 30</td>
</tr>
<tr>
<td></td>
<td>Elm spanworm</td>
<td>Various broadleaf trees</td>
<td>June 1-30</td>
</tr>
</tbody>
</table>
Table 5.3 (continued). Optimum biowindows for aerial sketchmapping various North American forest insects (redrafted from Klein et al. 1983)

<table>
<thead>
<tr>
<th>Forest Region</th>
<th>Insect</th>
<th>Host</th>
<th>Approx. Biowindow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southeast</td>
<td>Southern pine beetle(^5)</td>
<td>Southern pines</td>
<td>June 1 - September 15</td>
</tr>
<tr>
<td></td>
<td>Ips engraver beetles(^5)</td>
<td>Southern pines</td>
<td>June 1 - September 15</td>
</tr>
<tr>
<td></td>
<td>Forest tent caterpillar</td>
<td>Broadleaf trees, especially water tupelo</td>
<td>April 20 - May 20</td>
</tr>
<tr>
<td></td>
<td>Balsam woolly adelgid</td>
<td>Balsam and Fraser firs</td>
<td>June 1 - September 15</td>
</tr>
<tr>
<td></td>
<td>Poplar tentmaker</td>
<td>Cottonwood</td>
<td>August 20 - September 30</td>
</tr>
<tr>
<td></td>
<td>Fall cankerworm</td>
<td>Broadleaf trees - oaks etc</td>
<td>June 15 - July 15</td>
</tr>
<tr>
<td></td>
<td>Elm spanworm</td>
<td>Broadleaf trees - oaks, hickories, etc</td>
<td>June 15 - July 15</td>
</tr>
<tr>
<td></td>
<td>Oak leaf tier</td>
<td>Oaks</td>
<td>June 15 - July 15</td>
</tr>
</tbody>
</table>

1 These periods will vary with latitude, elevation, and climatic conditions.
2 In the southern part of its range, western pine beetle may have up to four generations annually.
3 In the southern part of their ranges, *Ips* spp, may have up to five generations annually.
4 Some Douglas-fir fade during the same season they are attacked, while others fade the following spring, requiring two flights to capture all of a current year’s mortality.
5 The southern pine beetle and the southern species of *Ips* may have up to seven generations annually.

In the Southeastern United States, where the southern pine beetle has anywhere from three to seven generations per year, it is necessary to make several flights per year to monitor outbreaks of this insect. Appropriate windows for survey depend on visibility of damage, the leafing out of broadleaf trees in spring and fall coloring of broadleaf trees and bald cypress (Billings and Ward 1984; Figure 5.4).
Figure 5.4. Seasonal detection patterns for southern pine beetle infestations. A: Gulf Coastal areas. B: Southeastern Piedmont and mountains. Dark arrows indicate recommended flight periods and clear arrows indicate optional flight periods (Billings and Ward 1984).

5.7.3. Number of Observers

The number of aerial observers used for a sketchmap survey varies with the type of aircraft, flight pattern and information needs. Most survey aircraft are four place and can accommodate a pilot and three observers. This configuration is best suited to grid pattern flying (see section 5.7.4.2.). Over more-mountainous terrain, two observers are often used with the more experienced observer seated in the right front seat functioning as both a navigator and observer. In some areas, only a single observer is used: this is the case in areas of especially rugged terrain where the reduced weight results in increased aircraft performance. In these cases, the single observer must be highly skilled (Tunnock 1978). Depending on terrain, visibility and occurrence of damage, aerial observers view a strip on either side of the aircraft that can vary from ½ to 2 miles in width (Aldrich et al. 1958, Wear and Buckhorn 1955).

5.7.4. Flight Patterns

The flight pattern of an aerial sketchmap survey varies according to the type of terrain, area to be covered and the level of accuracy required. There are basically two types of flight patterns: contour and grid patterns (Figure 5.5). Regardless of the pattern selected, the aerial observers should always know the exact location of the aircraft with respect to the ground. This can be done by tracing the actual path of the aircraft on the survey map prior to flight (Klein et al. 1983) or through use of an airborne GPS.
5.7.4.1. – Contour Flying. Contour flying is done in areas of relatively steep, well defined topography or in situations where rather detailed information is needed. In contour flying, the aircraft is usually flown in a left-hand pattern, generally parallel to the drainage patterns rather than across them. The principal observer, sitting in the front right seat of the aircraft, has the drainage always to his or her right. The observers then survey those portions of the drainage visible from the front and right hand windows of the aircraft (McConnell et al. 2000).

5.7.4.2. – Grid Flying. The grid pattern is generally flown in level, poorly defined terrain such as is typical of much of the southeastern and central U.S. In maintaining a grid pattern, the aircraft is flown in a series of straight lines at specified distances ranging from one to six miles. If two observers are in the aircraft, each observes a distance of one half the flight line interval. Obviously, the closer the flight line spacing, the more accurate the survey (Table 5.2; Aldrich et al. 1958).

Flight lines are usually predetermined and drawn on the survey maps prior to the flight. The beginning and ending points of each flight line should be easily defined from the air, such as a highway or power line running more or less perpendicular to the direction of flight (Billings and Ward 1984).
Visual orientation along a long flight line can be difficult, especially over extensive areas of forest with few cultural features. Use of aircraft navigational systems such as LORAN-C and, more recently, GPS are now being used to help aerial observers with orientation.

The ratio of contour to grid pattern flying varies according to the steepness of the terrain. In the Northern Rockies, most sketchmapping is done by contour flying (McConnell 1995b), whereas, in the Intermountain states, a combination of contour and grid flying is used (Knapp 1995). In the Pacific Northwest, about 30 percent of the forests of Washington are flown by a contour pattern and 70 percent by a grid pattern, and virtually all of Oregon is covered by grid flying (Bridgwater 1995).

### 5.7.5. Data Recording

Forest damage detected during aerial sketchmap surveys is recorded as points or polygons on survey maps with an accompanying numerical designator indicating the aerial observer’s estimate of the causal agent based on the damage signature. In the case of tree mortality, such as caused by bark beetles, a two-number code may be used (e.g., 5-25), with the first number being the causal agent code and the second an estimate of the number of fading crowns. If counts of faders are not made, an intensity code of L (light), M (moderate), or H (heavy) may be used. A coding protocol for mapping southern pine beetle infestations is shown in Figure 5.6 (Billings and Ward 1984) and the insect portion of the coding system for the annual aerial detection survey used by the USDA Forest Service, Northern Region is shown in Table 5.4.

<table>
<thead>
<tr>
<th>Source of Information</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial aerial survey</td>
<td>20/1</td>
<td>New spot with 20 trees and priority 1 for ground check (color indicates date of flight)</td>
</tr>
<tr>
<td>Ground check information</td>
<td>15/3</td>
<td>Spot found to be inactive upon ground check (use to update flight maps prior to next flight)</td>
</tr>
<tr>
<td>Control Information</td>
<td>50/1</td>
<td>Spot controlled since last flight (use to update maps prior to next flight)</td>
</tr>
<tr>
<td>Follow-up flight</td>
<td>20/4</td>
<td>Previously seen spot that appears to be inactive from the air with bare trees or red crowns or both but no yellow crowns</td>
</tr>
<tr>
<td>Follow-up flight</td>
<td>100/1</td>
<td>Controlled spot that is observed from the air to have a breakout with 20 active trees</td>
</tr>
<tr>
<td>Follow-up flight</td>
<td>B.O./20</td>
<td>Previously seen spot updated from 10 to 40 active trees and priority 4 to priority 1.</td>
</tr>
</tbody>
</table>

Figure 5.6. Suggested mapping symbols to be used on southern pine beetle flight maps (Billings and Ward 1984).
Table 5.4. Coding key used for forest insect damage on aerial survey maps by the USDA Forest Service–Northern Region.*

<table>
<thead>
<tr>
<th>Code</th>
<th>Insect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>BARK BEETLES</strong></td>
</tr>
<tr>
<td>1</td>
<td>Douglas-fir beetle</td>
</tr>
<tr>
<td>2</td>
<td>Engelmann spruce beetle</td>
</tr>
<tr>
<td>3</td>
<td>Pine engraver - ponderosa pine</td>
</tr>
<tr>
<td>4</td>
<td>Mountain pine beetle - white pine</td>
</tr>
<tr>
<td>5</td>
<td>Mountain pine beetle - ponderosa pine</td>
</tr>
<tr>
<td>6</td>
<td>Mountain pine beetle - lodgepole pine</td>
</tr>
<tr>
<td>7</td>
<td>Mountain pine beetle - whitebark or limber pine</td>
</tr>
<tr>
<td>8</td>
<td>Western pine beetle</td>
</tr>
<tr>
<td>9</td>
<td>Fir engraver</td>
</tr>
<tr>
<td>10</td>
<td>Douglas-fir engraver beetle</td>
</tr>
<tr>
<td>11</td>
<td>Western balsam bark beetle - subalpine fir</td>
</tr>
<tr>
<td>12</td>
<td>Unidentified bark beetle</td>
</tr>
<tr>
<td>13</td>
<td>Pine engraver - lodgepole pine</td>
</tr>
<tr>
<td></td>
<td><strong>DEFOLIATORS AND OTHER INSECTS</strong></td>
</tr>
<tr>
<td>17</td>
<td>Balsam woolly adelgid</td>
</tr>
<tr>
<td>18</td>
<td>Spruce budworm</td>
</tr>
<tr>
<td>21</td>
<td>Larch casebearer</td>
</tr>
<tr>
<td>22</td>
<td>Douglas-fir tussock moth</td>
</tr>
<tr>
<td>23</td>
<td>Pine butterfly</td>
</tr>
<tr>
<td>24</td>
<td>Black-headed tussock moth</td>
</tr>
<tr>
<td>25</td>
<td>Larch bud moth</td>
</tr>
<tr>
<td>26</td>
<td>Pine looper</td>
</tr>
<tr>
<td>27</td>
<td>Pine tortrix</td>
</tr>
<tr>
<td>28</td>
<td>Tent caterpillars</td>
</tr>
<tr>
<td>29</td>
<td>Leaf beetles</td>
</tr>
<tr>
<td>30</td>
<td>Larch sawfly</td>
</tr>
<tr>
<td>31</td>
<td>Hemlock looper</td>
</tr>
<tr>
<td>32</td>
<td>Larch looper</td>
</tr>
<tr>
<td>33</td>
<td>Western false hemlock looper</td>
</tr>
<tr>
<td>34</td>
<td>Pine needle-sheath miner</td>
</tr>
<tr>
<td>35</td>
<td>Pine sawflies</td>
</tr>
<tr>
<td>36</td>
<td>Pine tussock moth</td>
</tr>
<tr>
<td>37</td>
<td>Cankerworms</td>
</tr>
<tr>
<td>38</td>
<td>Variable oak leaf caterpillar</td>
</tr>
<tr>
<td>39</td>
<td>Unidentified defoliator</td>
</tr>
<tr>
<td>74</td>
<td>Lodgepole pine needle miner</td>
</tr>
</tbody>
</table>

*Codes also exist for forest diseases and abiotic damage.
5.7.6. Ground Checking

Ground checking should be an integral part of aerial sketchmap surveys. Purpose of ground checks are to confirm the aerial observer’s diagnosis of the causal agent and the spatial and classification accuracy of the survey information. Like aerial sketchmapping, ground checking is an informal process that involves visiting sites mapped from the air on the ground and gathering data on causal factors, numbers of fading trees, severity of defoliation, etc. During southern pine beetle outbreaks in the southeastern U.S., all spots classified as being “active” from the air are ground checked to verify presence of trees containing beetle brood. In the case of defoliating insects, it is often possible to map additional areas of very light damage not visible from the air. This can sometimes add up to 50 percent more area to estimates of the total infested area. Because of limited time and personnel, and other work priorities, the intensity of formal ground checking has declined. Ground checking is still done, however, in instances were damage is discovered that was not present during the previous survey or when damage of an unknown or unfamiliar signature is mapped.
5.8. END PRODUCTS OF AERIAL SKETCHMAP SURVEYS

The primary products of aerial sketchmap surveys are maps showing location of forest damage and reports or tables of statistical summaries of pest conditions.

The rough survey maps, showing location of areas of forest damage by causal agent, are available immediately after the aerial survey is completed. Additional time is required, however, to produce “clean” maps, which are sent to National Forests, National Parks, Indian reservations, and other units included in the surveys. During the past 10 years, GIS has become a standard tool for map production (Figure 5.7) data analysis, storage, and development of historical databases using sketchmap data. Presently, all Forest Service Regions and many state forestry agencies have GIS capacities for data manipulation and storage of aerial sketchmap-derived forest damage information (McConnell 1995a). In the Pacific Northwest Region, for example, polygons and their attributes are hand transferred from the flight maps to mylar, scanned into a GIS, and edited. The GIS produces cronoflex overlays, which display the labeled damage polygons. These are used to produce paper copies of damage maps, which are distributed to federal, state, and private land managers (Bridgewater 1995). As of 1995, data from annual aerial detection surveys in the Pacific Northwest back to 1980 have been entered into the Region’s GIS with a current goal to enter data back to 1970 (Johnson 1995).

![Figure 5.7. Section of an aerial survey map of the Nezperce National Forest, Idaho, showing location of damaged areas. The first number for each polygon is the pest code (see table 5.4) and the second number is the estimate of dying (fading) trees. This map was produced from data entered into a GIS (map courtesy of T. McConnell, USDA Forest Service, Missoula Montana).]
The second product of aerial sketchmap surveys is statistical data and reports summarizing the status of forest damage. These reports may take many forms, including summaries for a forested area such as a national forest; statewide, regional, or national summaries for a specific pest; or multi-year data tables showing pest trends over time. Sample data tables for display of data on the results of an aerial survey for southern pine beetle in the southeastern U.S. and for western spruce budworm in the Pacific Northwest Region are shown in Tables 5.5 and 5.6. Data tables can be produced either directly or indirectly from the raw data entered into the GIS. In the Pacific Northwest Region, for example, the GIS data is imported into the database software Paradox for preparation of data tables. These are also made available to land managers, used to monitor trends, and to prepare regional summaries of pest conditions.

Table 5.5. Summary of aerial sketchmap data for southern pine beetle damage from two counties in east Texas (Billings and Ward 1984).

<table>
<thead>
<tr>
<th>County</th>
<th>Numbers of spots by size class (number of red-tops and faders)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Polk</td>
<td>54</td>
</tr>
<tr>
<td>Jackson</td>
<td>37</td>
</tr>
<tr>
<td>TOTALS</td>
<td>91</td>
</tr>
</tbody>
</table>

Table 5.6. Regional summary of area defoliated by western spruce budworm, in acres, in the Pacific Northwest Region, 1977-1979 (Dolph 1980).

<table>
<thead>
<tr>
<th>Year</th>
<th>Administrative Unit *</th>
<th>Oregon</th>
<th>Washington</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977</td>
<td>Fremont National Forest</td>
<td>6,910</td>
<td></td>
<td>6,910</td>
</tr>
<tr>
<td></td>
<td>Warm Springs Indian Reservation</td>
<td>18,890</td>
<td></td>
<td>18,890</td>
</tr>
<tr>
<td></td>
<td>Okanogan National Forest</td>
<td>269,120</td>
<td></td>
<td>269,120</td>
</tr>
<tr>
<td></td>
<td>Wenatchee National Forest</td>
<td>793,510</td>
<td></td>
<td>793,510</td>
</tr>
<tr>
<td></td>
<td>Colville Indian Reservation</td>
<td>910</td>
<td></td>
<td>910</td>
</tr>
<tr>
<td></td>
<td>Yakima Indian Reservation Northern Cascades National Park</td>
<td>2,620</td>
<td>109,660</td>
<td>109,660</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>25,800</td>
<td>1,175,820</td>
<td>1,201,620</td>
</tr>
<tr>
<td>1978</td>
<td>Warm Springs Indian Reservation</td>
<td>5,980</td>
<td></td>
<td>5,980</td>
</tr>
<tr>
<td></td>
<td>Okanogan National Forest</td>
<td>106,910</td>
<td></td>
<td>106,910</td>
</tr>
<tr>
<td></td>
<td>Wenatchee National Forest</td>
<td>62,120</td>
<td></td>
<td>62,120</td>
</tr>
<tr>
<td></td>
<td>Northern Cascades National Park</td>
<td>23,940</td>
<td></td>
<td>23,940</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>5,980</td>
<td>192,970</td>
<td>198,950</td>
</tr>
<tr>
<td>1979</td>
<td>Warm Springs Indian Reservation</td>
<td>28,590</td>
<td></td>
<td>28,590</td>
</tr>
<tr>
<td></td>
<td>Okanogan National Forest</td>
<td>239,770</td>
<td></td>
<td>239,770</td>
</tr>
<tr>
<td></td>
<td>Wenatchee National Forest</td>
<td>93,120</td>
<td></td>
<td>93,120</td>
</tr>
<tr>
<td></td>
<td>Northern Cascades National Park</td>
<td>41,010</td>
<td></td>
<td>41,010</td>
</tr>
<tr>
<td></td>
<td>Colville Indian Reservation</td>
<td>4,170</td>
<td></td>
<td>4,170</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>28,590</td>
<td>378,070</td>
<td>406,660</td>
</tr>
</tbody>
</table>

*Includes lands of all ownerships within and adjacent to the National Forest.
5.9. **SAFETY**

Safety is a major consideration anytime small aircraft are used in remote, often mountainous terrain, and must be a key item in planning and executing aerial sketchmap surveys. All aircraft considered airworthy must meet FAA specifications for performance and safety. Many federal and state agencies (including USDA Forest Service) supplement these specifications with their own requirements. These may also include pilot qualifications, number of hours that can be flown during a given time period, minimum flying heights, etc., and should be specified in aircraft rental agreements.

In addition to aircraft and pilot qualifications, other important safety considerations (taken from Klein et al. 1983) include the following.

1. A flight plan should be filed prior to departure whenever possible. In remote airstrips, this may not be possible; however, they can be filed shortly after the survey team has taken off. Deviations from the intended plan should also be filed and the plan should be promptly closed at the end of the flight.

2. Many USDA Forest Service and State survey aircraft establish additional radio communication by the use of local-network portable radios. The designated “senior” aerial observer establishes a reporting schedule with a ground station and provides position reports at specified time intervals. If radio communication is not possible, a telephone check-in system should be established with the unit supervisor or duty station. These calls should be made after each flight and recorded in a daily log. Information logged should include the aircraft type, color, Federal Aviation Administration (FAA) number, and the area scheduled for survey the following day. If an airport change is planned, the new airport location and expected time of arrival should also be logged. This should *never* be left to chance.

3. A radio locator beacon, fire extinguisher, first aid kit, flashlight, and FAA approved shoulder harnesses should be standard equipment for each survey aircraft. If aerial surveys are to be undertaken in remote, inaccessible areas, personal survival equipment should be taken and stowed in the aircraft’s baggage compartment. This could include a warm jacket, stocking hat, boots, pocket knife and two days of lightweight (dehydrated or freeze dried food). Contents of an emergency supply kit may vary depending on the area to be flown and should be developed at the local level.

4. Some organizations require that personnel flying in helicopters and fixed wing aircraft wear fire retardant (NOMEX) clothing. This includes one-piece coveralls and gloves. The coveralls should fit rather loosely and be large enough to fit over regular clothing. It is also important to wear only natural fibers (cotton, wool) as part of regular clothing during flights because synthetic fabrics such as nylon, rayon, or dacron blends can melt when exposed to high temperatures and cause severe burns. A crash helmet will provide additional protection.
5. The number of personnel in a survey aircraft should be kept at a minimum. Extra persons add weight and reduce aircraft performance at higher elevations.

Safety protocols for aerial sketchmap surveys should be described in detail in aviation management plans.¹

¹See USDA Forest Service (1999a) for an example of an aviation management plan.
5.10. ELECTRONIC ENHANCEMENTS TO AERIAL SKETCHMAPPING

Significant advances in computer technology, GPS, and GIS has led to interest in the development of electronic enhancements, both in Canada and the U.S., to allow direct recording of forest damage on maps stored in a laptop computer during aerial sketchmap surveys.

The Provincial Forest Service of British Columbia, Canada, developed a digital aerial sketchmapping system. This system operates on a standard laptop computer and allows the aerial observer to sketch forest damage directly onto maps stored in the computer by using a standard trackball mouse. Software developed by the Forest Service of British Columbia uses Microstation MDL programming language, and requires a full installation of the Microstation software. Data input and user-interface features include aircraft position displayed on the computer screen as an icon, background map rotation based on the aircraft’s direction of travel, and attributing of features using pre-programmed function keys. Some disadvantages of this system include the small size of the screen on the laptop PC, lack of screen brightness, awkwardness of the mouse pointing device, and data incompatibilities between Microstation and Environmental Systems Research Institute (ESRI) Arc/Info, the standard GIS software used by USDA Forest Service. This system is also slow and cumbersome (Schrader-Patton 1999).

The Remote Sensing Applications Center (RSAC), USDA Forest Service, initiated a project in 1995 to develop a digital aerial sketchmap system using existing components that could be interfaced. The following system requirements were identified:

1. The map display must be linked to a GPS receiver so that an icon on the screen display represents the current aircraft position.
2. The map display must update quickly to accommodate aircraft ground speeds of 130 mph.
3. The screen must be viewable under a variety of light conditions, including full sunlight, and also display in full (256) color.
4. The viewable screen size must be at least 10.4 inches, measured diagonally.
5. The software must be able to:
   - Digitize points, lines and polygons including nested and overlapping polygons.
   - Attribute digitized features quickly and easily.
   - Edit feature attributes.
   - Allow the user to define the feature attributes to be collected.
   - Collect a GPS log of the flight.
   - Allow the user to zoom to different map scales.
   - Accept common raster and vector data types as background maps.
   - Export files in a format that can be easily imported into ESRI Arc/Info.
- Save data automatically to the computer’s disk.
- Update the screen map display based on the GPS position and aircraft heading.

6. Hardware should be operational in moderately harsh conditions (32-120°F, high humidity, dusty conditions)

7. Primary input device must be a touchscreen with stylus.

A first stage system has been developed and is presently being evaluated. The system software is currently a modified version of GeoLink PowerMap by GeoResearch, Inc., of Billings, Montana. This software displays the aircraft’s position as an icon on the map display along with user-defined features presented as button icons. The aerial observer selects the icon corresponding to the feature seen from the aircraft, sketches the feature on the computer screen and records the feature attributes by selecting the “log” button. When the aircraft icon advances to the edge of the screen, the map display updates with the aircraft icon moving to the center of the map display on the screen. Upon completion of the sketchmap mission, a translation step converts the sketched features into ESRI shapefiles. These files are then copied to a floppy disk for transfer to the GIS. USGS 100,000-scale topographic maps, converted to a digital raster graphics (DRG) format, are used as the map base. Hardware presently consists of a laptop computer with a 133 Mhz Pentium processor and 48 megabytes of random-access memory, an external touchscreen monitor, and a GPS receiver. The system is powered independently of the aircraft with a 12-volt battery and a DC/AC power inverter. The GPS receiver signals enter the personal computer via a PCMCIA card serial port connection. Most of the hardware is installed in the cargo area of the survey aircraft or in the rear passenger seat. When the screen is functioning, the aerial observer operates the software holding the touchscreen in his or her lap.

The existing hardware assembly has the advantage of relatively low cost and flexibility. Total cost is less than $8,000. Both the laptop computer and GPS receiver can be upgraded as faster processors and more memory become available. The hardware is still somewhat awkward and cumbersome, however, with many components and cables in the confined space of a small aircraft.

Potential advantages of the digital aerial sketchmapping system include cost savings due to reduced time spent in post-processing data and quicker delivery of data to the field (Schrader-Patton 1999).
5.11. QUALITY ASSESSMENT AND QUALITY CONTROL

A new development in aerial sketchmapping in recent years is increased emphasis on assessment of the quality and quality control. This has led to the development of aerial survey standards in the United States that define damage types, methods of coding, and quality control. These standards also define sketchmapper training and certification standards and mandate annual training, including safety procedures, damage signatures, mapping thresholds, severity ratings, coding standards and coordination, and evaluation. Also mandated is a post-survey evaluation to review and summarize the past survey season and define needed changes (USDA Forest Service 1999b).
6. AERIAL PHOTOGRAPHY—PRINCIPLES AND PARAMETERS

Aerial photography is another remote sensing tool that has been widely used in forest health protection. This chapter discusses some of the basic parameters to be considered when using aerial photographs for forest health protection. These include camera formats, lenses, films, and photographic scales. The geometry of aerial photographs is also reviewed in sufficient detail to allow a forest health specialist to plan and conduct an aerial photography mission. Examples of how aerial photographs have been used in forest health protection are reviewed in chapter 7.

6.1. STRENGTHS AND WEAKNESSES

Of all of the remote sensing tools presently available, photography produces images of the highest resolution. Provided that aerial photographs are taken with the proper lens and film and from an appropriate flying height, it is possible to resolve individual tree crowns. This is of vital importance to the forest health specialist, who often looks for subtle crown changes indicative of declining or poor tree and stand health.

Aerial photographs and the other remote sensing tools discussed in subsequent chapters have an advantage over aerial sketchmapping in that they provide a permanent record of conditions over an area at a given point in time. The cost of aerial photograph acquisition, on the other hand, is more expensive than aerial sketchmapping. Moreover, since aerial films require special processing and must be shipped to a company that provides this service, there is a time delay before the photographs are available for interpretation.

6.2. DEFINITION OF SOME KEY TERMS

Aerial photographs have many uses, including map production, cadastral surveys (establishment and monitoring of property boundaries), military reconnaissance, and natural resources monitoring. The science of making measurements from photographs is known as photogrammetry, and is a precise engineering science. Included in this section are descriptions of some the common terminology used in photogrammetry as defined by the American Society of Photogrammetry and Remote Sensing (ASPRS) (Thompson 1966). These terms will be encountered frequently throughout the remainder of this publication.

Fiducial marks: Index marks, usually four, rigidly connected with the camera lens through the camera body that form images on the negative and can be used to define the principal point on an aerial photograph.

Focal length: The distance from the camera lens element to the film plane, expressed in millimeters (mm), centimeters (cm), or inches.

Image motion: A blur or smear on a photographic image caused by the forward motion of the aircraft during photograph acquisition. This can occur if a slow shutter speed is used or if the photography mission is flown at too low an elevation. Some modern aerial cameras are
equipped with an **image motion compensator** that allows the film to move at a forward speed equivalent to the ground speed of the aircraft.

**Intervalometer:** A timing device for automatically operating the shutter of a camera at selected intervals.

**Mosaic:** An assembly of aerial photographs whose edges have been torn or cut and matched to form a continuous photographic representation of a portion of the Earth’s surface. Airborne videography and digital images (chapter 8) can also be combined into a mosaic using computer software.

**Nadir:** A point on the Earth’s surface directly beneath the observer. In the context of an aerial photograph or other airborne image, it is the point on the ground vertically beneath the perspective center of the camera lens.

**Scale:** The ratio of a distance on a photograph or map to its corresponding distance on the ground. Scale may be expressed as a ratio (1:100,000), a representative fraction (1/100,000), or an equivalence (1 millimeter = 100,000 millimeters, 1,000 meters, or 1 kilometer).

**Stereoscopy:** The science and art that deals with the use of binocular vision or observation of a pair of overlapping photographs to produce a three-dimensional view.

**Stereoscope:** An optical instrument for helping an observer to view photographs or diagrams to obtain the mental impression of a three-dimensional model.

**Oblique aerial photo:** A photograph taken with the camera axis intentionally directed between the horizontal and the vertical. A **high oblique photograph** is one in which the apparent horizon is included in the field of view and a **low oblique photograph** is one in which the apparent horizon is not included in the field of view.

**Principal point:** The point that represents the exact geographic center of an aerial photo. On a vertical aerial photo, the principal point is directly below the camera lens. Provided that the axis of the camera is truly vertical, this point represents the geographic point at the exact center of the photograph, or the “nadir” point.
**Vertical aerial photo:** An aerial photograph made with the camera axis at vertical, or as nearly vertical as possible, in an aircraft.
6.3. FORMATS
Cameras for aerial photography are available in several film sizes and formats. **Large-format cameras** specifically designed for aerial photography tend to take large film sizes so that the resulting photograph will cover a large area of land and be of the highest possible resolution without enlargement. Nine-inch **mapping-format cameras**, somewhat smaller in format, are also used for aerial photography. Other cameras, such as 35-mm and 70-mm cameras, have been adapted for use in aircraft, and are commonly referred to as **small-format cameras**.

6.3.1. Nine-Inch Mapping Format
Nine-inch mapping (frame) cameras are the most widely used of aerial cameras. These cameras expose a 9-by-9 inch (23-by-23 cm) segment of 9.5-inch aerial film each time a photograph is taken. Resulting photographs have the advantage of covering reasonably large areas of land at a high spatial resolution.

A number of 9-inch camera models and lens configurations (section 6.4) are available. These range from the relatively simple reconnaissance cameras originally developed for military applications during World War II, such as the K-17, to sophisticated mapping cameras calibrated to high engineering standards and equipped with image motion compensators, such as those produced by the Wilde and Zeiss corporations.

Most forest health applications of aerial photography have used 9-inch frame cameras.

6.3.2. Small Format Photography
Aerial photographs, taken with 35-mm and 70-mm cameras, have been used in natural resource applications of remote sensing and provide a low-cost alternative to 9-inch mapping cameras for aerial photograph acquisition. Moreover, they provide an opportunity to acquire stereoscopic photographs at much larger scales than can be obtained with 9-inch mapping cameras because of the time required to cycle 9-inch film through the film plane. Many brands of 35-mm and 70-mm cameras, equipped with wide-angle, normal, and telephoto lenses used for ground-based photography, are readily available and can be placed in specially designed camera mounts for acquisition of stereoscopic vertical aerial photographs or hand held for oblique photographs. In addition, a number of 70-mm camera systems, such as those produced by the Hulcher Corporation, have been developed specifically for aerial photography (Aldrich 1966, Heller et al. 1959a).

A disadvantage of small-format photography is the relatively small land area covered by a single photograph (Table 6.1). This is of particular concern when taking photographs over remote forests where there are few distinguishing landmarks to pinpoint photograph location, making location of ground plots difficult, if not impossible. Pinpointing ground location can be facilitated, however, by interfacing a GPS receiver with a small-format camera, as has been done with airborne videography and digital camera systems (chapter 7). Small format camera systems are currently of greatest interest in forest plantations or special use areas where specific targets can be identified on the ground and photographed.
Table 6.1. Comparison of land area covered by 35-mm, 70-mm and 9-inch aerial photographs at photographic scales commonly used in forest health applications of remote sensing

<table>
<thead>
<tr>
<th>Photo scale</th>
<th>35-mm</th>
<th>70-mm</th>
<th>9-inch (230 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acres</td>
<td>Hectares</td>
<td>Acres</td>
</tr>
<tr>
<td>1:2,000</td>
<td>0.85</td>
<td>0.34</td>
<td>3.97</td>
</tr>
<tr>
<td>1:4,000</td>
<td>3.39</td>
<td>1.37</td>
<td>15.89</td>
</tr>
<tr>
<td>1:6,000</td>
<td>7.62</td>
<td>3.08</td>
<td>35.76</td>
</tr>
<tr>
<td>1:8,000</td>
<td>13.55</td>
<td>5.48</td>
<td>63.57</td>
</tr>
<tr>
<td>1:12,000</td>
<td>30.48</td>
<td>12.34</td>
<td>143.02</td>
</tr>
</tbody>
</table>

The small land area covered by small-format photography has limited the use of this technology in forest health applications primarily to tests and demonstrations. Thirty-five-mm aerial photographs are widely used during aerial sketchmap missions to photograph examples of forest damage encountered during these surveys and to provide materials for training aerial observers. Vertical 35-mm aerial photographs (scale 1:4,000) were evaluated for mapping damage caused by the mountain pine beetle in lodgepole pine forests in the USDA Forest Service Intermountain Region and were found to be helpful in providing resource managers with timely synopses of insect damage, sampling damage, and planning control operations (Klein 1970). Oblique 35-mm photographs have also been used to show differences in levels of insect-caused defoliation between small blocks treated with insecticides and surrounding untreated areas (White et al. 1978, Figure 6.1).

Seventy-mm color aerial photographs, taken at a scale of 1:500 over eastern white pine plantations in northern New York resolved leader damage caused by the white pine weevil, (*Pissodes strobi*) (Heller et al. 1959). In a similar study conducted in British Columbia, Canada, both color and CIR 70-mm aerial photographs taken at a scale of 1:1,200 were evaluated for ability to detect leader damage caused by *P. strobi* in Sitka spruce plantations, and indicated that CIR photographs were superior for discriminating damage (Carlson and McLean 1984). Leader damage caused by this insect is virtually impossible to see and classify during aerial sketchmapping missions.

An innovative approach to using 70-mm aerial photographs is to use a pair of cameras spaced at a known horizontal distance and mounted on a boom suspended from a helicopter or on the wing tips of a fixed wing aircraft. Stereo photographs are obtained by simultaneously exposing the film in two cameras at once, and photographic scale can be calculated from the ratio of the photographic base over actual air base. This approach has been used for inventories of mountain pine beetle damage in western Canada (Harris et al. 1982) (chapter 7, section 7.1.1.3.) and for assessment of jarrah dieback in Australia (Spencer 1998; chapter 10, section 10.1).
Figure 6.1. A pair of color and CIR 35-mm oblique photographs taken of a test plot treated with a nuclear polyhedrosis virus (NPV) for control of Douglas-fir tussock moth, *Orgyia pseudotsugata*, Wallowa Whitman National Forest, Oregon.
6.3.3. Large-Format Photography

Large format photographs, taken from cameras mounted in high-altitude reconnaissance aircraft (Figure 6.2) have also been used in forest health protection. The aircraft and camera systems are available through NASA. Two large format camera systems are available:

- Hycon HR 732 9-by-18-inch frame camera
- Itek KA80A and IRIS II optical bar panoramic camera systems.

6.3.3.1. Hycon 732 Frame Camera. The Hycon 732 9-by-18-inch frame camera takes standard 9.5 inch aerial films but the frame size is twice that of a standard format mapping camera and is equipped with a 24-inch focal length lens. The performance of this camera system has been evaluated for forest health protection (Klein et al. 1978) but has not been widely used. Its primary use has been to acquire CIR coverage of National Forests for resource photography.

Figure 6.2. A NASA ER-2 high-altitude reconnaissance aircraft (photo courtesy of NASA).

6.3.3.2. Panoramic Cameras. Panoramic camera systems were first used in forest health protection in the mid 1970s. The first camera system available through NASA was the Itek KA 80 A. Several years later, an improved version, the Itek IRIS-II panoramic camera, was made available. Panoramic cameras have several features of interest in forest health protection. First and foremost is the ability of these cameras to produce **high resolution stereoscopic photographs** from high altitudes. Moreover, the ER-2 reconnaissance aircraft can cover **large areas in a short time**. For example, during a 1978 test of this system in California, a 4,400-square-mile test site was photographed in 16 minutes of flying time (Klein et al. 1978). This capability makes it possible to acquire aerial photographic coverage of large areas of forest damage (e.g., millions of acres) within the narrow biowindow often specified for forest damage assessment. Panoramic aerial cameras achieve large area coverage at a high image resolution by using only the center of a narrow field of view.
view lens and effectively sweeping the lens across the terrain. A large lens aperture (f/3.5) provides sufficient illumination for exposure of slow speed, high resolution aerial films (Liston 1982).

Both the KA80A and IRIS II camera systems produce images on standard 5-inch wide aerial films. Size of an individual photograph frame is 4.5 by 50 inches for the KA80A, which has a lateral coverage of 120°. Two versions of the IRIS II camera are available; one with a lateral coverage of 140° (photo frame size = 4.5 by 57 inches), and a system modified for forest damage assessment with a lateral coverage of 90° (4.5 x 38 inches). These cameras are equipped with 24 inch focal length f/3.5 lenses that produce a nadir scale of 1:30,000 from a flying height of 60,000 ft AGL. At 60° from nadir, in track photographic scale is 1:60,000 and cross track photographic scale is 1:120,000. Forward ground coverage is 1.8 nautical miles at nadir and 17.1 nautical miles at 60° of nadir (Liston 1982; Figure 6.3).

The change in photographic scale and the unconventional size of the KA 80 A and IRIS II film products create some unusual challenges in photointerpretation and film handling.

Mathematical models and associated computer programs have been developed to correct for changes in photographic scale across a photograph frame. PANGRID generates an equal area clear plastic grid overlay that can be used to correct a panoramic photograph for changes in scale. Grid cell size, grid scale, and scan angle limits can be specified by the user. This model assumes a flat Earth and constant flying height. Grids produced by PANGRID can be used interchangeably from frame to frame (Liston 1982).
Many forested areas occur in mountainous terrain. To integrate changes in elevation with changes in photographic scale, a Photographic Mapping System model was developed. This system uses Defense Mapping Agency (DMA) digital terrain software. Equal area grids generated by this software are unique to each frame of photography (Liston 1982).

The optical bar panoramic camera systems were widely used for a number of forest health applications during the mid 1970s and 1980s (chapter 7). A CIR film (Kodak SO-131) especially designed for high-altitude reconnaissance missions was used. This film was discontinued about 1990 because of manufacturing problems, and there has been virtually no use of this camera system for forest health protection since that time. A new high-altitude CIR film (Kodak SO-060) is currently available but has not yet been evaluated for forest health protection applications.
6.4. LENSES

In aerial photography, the focal length of the camera lens is the most important lens characteristic in terms of photography mission planning. The focal length of the lens, in combination with flying height, determines the scale of the resulting photographs.

Lenses in a wide range of focal lengths are available for small-format (35- and 70-mm cameras). Nine-inch aerial mapping cameras are generally equipped with either a 6-inch (15 cm) or 12-inch (30 cm) lens. The 8.25-inch (21-cm) focal length lens is less common, but several cameras equipped with 8.25-inch lenses are available in the USDA Forest Service for project level aerial photography. Consequently, this lens has been widely used for acquisition of photographs for forest health or forest damage assessments. The large format cameras discussed in the preceding section are equipped with 24-inch focal length lenses.

Lens focal length and film format affect camera geometry and interpretation and measurement values taken from the photographs. For a given film format (e.g., 9-inch) and scale, longer focal length lenses provide better penetration of the forest canopy because there is less image displacement to obscure understory and surrounding trees. Image displacement in vertical aerial photographs is radial from the photograph center (the principal point), proportional to object height and distance from the image to the photograph center, and is inversely proportional to flying height above the terrain. Therefore, as flying height increases, radial displacement decreases.

Flying higher with a longer focal length lens is a way to reduce displacement while maintaining image resolution (Figure 6.4). Another alternative is to use a small-format camera with a long focal length lens at lower elevations. When using 9-inch format aerial cameras equipped with 6-inch focal length lenses, the largest effective photographic scale at which image displacement does not adversely affect interpretability of the photograph is about 1:8,000. With 8.25- and 12-inch focal length lenses, scales of 1:4,000 and 1:6,000 can be obtained with minimum image displacement.
Figure 6.4. Effects of lens focal length on image displacement for aerial photographs of the same scale (redrawn from Spencer 1998).
6.5. SCALE

As defined earlier, scale is the ratio of a distance on a photograph or map to its corresponding distance on the ground.

6.5.1. Determining the Scale of an Aerial Photo

In aerial photogrammetry, scale is a function of the focal length of the camera lens \( f \) and the flying height above ground level (AGL), usually expressed as \( H \). The scale \( S \) of an aerial photograph can be determined from the following equation:

\[
S = \frac{f}{H}
\]

Knowing the focal length of the camera and the flying height, it is easy to determine the resulting scale.

Exercise Problem: What is the scale of an aerial photograph to be taken from a flying height of 6,000 feet with a 9-inch aerial mapping camera equipped with a 6-inch focal length lens:

Expressed as a unit equivalent:

\[
S = \frac{6 \text{ inches}}{6,000 \text{ feet}} = \frac{1 \text{ inch}}{1,000 \text{ feet}} \text{ or } 1 \text{ inch} = 1,000 \text{ feet}
\]

Expressed as a representative fraction:

\[
S = \frac{6 \text{ inches}}{6000 \text{ feet}} = \frac{0.5 \text{ feet}}{6,000 \text{ feet}} \text{ or } 1:12,000
\]

Now determine the scale of an aerial photograph to be taken from a flying height of 6,000 feet with a 9-inch camera and a 12-inch focal length lens:

Expressed as a unit equivalent:

\[
S = \frac{12 \text{ inches}}{6000 \text{ feet}} = \frac{1 \text{ inch}}{500 \text{ feet}} \text{ or } 1 \text{ inch} = 500 \text{ feet}
\]

Expressed as a representative fraction:

\[
S = \frac{12 \text{ inches}}{6000 \text{ feet}} = \frac{1 \text{ foot}}{6000 \text{ feet}} \text{ or } 1:6,000
\]

Note: For a 6-inch focal length lens, the photographic scale is \( \frac{1}{2} \) of the flying height above AGL in feet. For a 12-inch focal length lens, the photographic scale is equal to the flying height elevation in feet.

The scale of an aerial photograph can be determined from a reliable map of the area covered by the photograph, provided that two points can be positively identified both on the photograph and the
map. Simply measure the distance between the two points on both the map and the photograph and compute photographic scale using the following relationship:

\[
\text{Photographic scale/map scale} = \frac{\text{photographic distance}}{\text{map distance}}
\]

**Exercise Problem:** A map scale is \textbf{1 inch = 800 feet} and a photograph covers a portion of the map area. The distance between two road intersections measures \textbf{4.34 inches on the photograph} and \textbf{1.55 inches on the map}. What is the scale of the photograph?

\[
\frac{1 \text{ inch}}{X \text{ feet}} = \frac{4.34 \text{ inches}}{800 \text{ feet}}
\]

\[
1 \text{ inch} / 800 \text{ feet} = \frac{1.55 \text{ inches}}{x \text{ feet}}
\]

\[
x = \frac{(1.55 \text{ inches} \cdot 800 \text{ feet})}{4.34 \text{ inches}} = 286 \text{ feet}
\]

\[
\text{scale} = \frac{1 \text{ inch}}{286 \text{ feet}} = 1:286, \text{ represented as a unit equivalent or}
\]

\[
1:(286 \cdot 12) = 1:3430, \text{ represented as a ratio scale.}
\]

### 6.5.2. Photographic Scales Commonly Used in Forest Health Protection

A range of photographic scales are used in forest health protection, depending on the data requirements. Many successful uses of aerial photography for detecting forest insect damage has been in the range of 1:600 to 1:12,000 (Heller 1971). If individual tree counts are needed, such as may be the case when assessing the level of tree mortality caused by bark beetles, or classifying trees with symptoms of decline, relatively large photographic scales in the range of 1:4,000 to 1:8,000 are the most suitable (Heller et al. 1959, Ciesla et al. 1967, Wear et al. 1966). Scales larger than 1:4,000 have been used with small-format photography (35- and 70-mm) but the recycling speed on 9-inch cameras is usually not fast enough to obtain aerial photographs with the minimum overlap (60 to 70 percent) required for stereoscopic coverage. Smaller scales, in the range of 1:12,000 to 1:30,000, work well for general damage mapping such as may be required for forest defoliators or windthrow. In one instance, defoliation of pine forests by pine butterfly, \textit{Neophasia menapia} was detected and mapped on 9-inch CIR aerial photographs taken from a NASA high-altitude aircraft at a scale of approximately 1:126,000 (Ciesla 1974).
6.6. **FILMS**

Many kinds of films are available for aerial photography. Aerial films are available in two forms. **Negative films** are processed to a negative image and then printed, usually on photographic paper as a **positive print**. **Positive transparency** or **reversal films** are processed directly to a positive image and viewed on a light table. Negative films are most widely used in aerial photography because they are easy to handle and view, especially when taken out in the field. A disadvantage of paper prints, however, is that some resolution is lost when the original image on the negative is transferred to photographic paper. When using positive transparencies, there is no loss of resolution. In addition, positive transparencies tend to have a higher contrast than paper prints. Therefore, positive transparencies have been most widely used in forest health protection.

6.6.1. **Panchromatic Films**

Panchromatic or black-and-white films are the most widely used aerial films for mapping and general resource photography. They have little or no value in forest health protection, however, because most forest damage appears as a change in color. Therefore their characteristics will not be discussed further in this publication.

6.6.2. **Color Films**

Several color films are available for aerial photography. The Eastman Kodak Company currently produces two color negative films and two color positive transparency films. These films have three layers, each sensitized to one of the three primary spectral regions of visible light: blue, green, and red. During processing, each layer produces a dye of a complementary color: yellow, magenta, and cyan, respectively. The amount of dye produced in any area is inversely related to the intensity of the radiation from the original scene. Therefore, each layer is a separate record of the brightness in a single primary color. When visible light is passed through the combinations of the three dyes, a close visual reproduction of the color of the original scene is formed. With a color negative film, the colors of the combined dye images will be complementary to the original scene and with a color positive transparency film, the images will be a close reproduction of the scene (Figure 6.5).

**Aerocolor negative film (2445)** is a medium-speed, very fine-grain color negative aerial film. This film is designed for general use in medium- to high-altitude aerial mapping and reconnaissance photography, and has a wide exposure latitude. Both black-and-white and color prints can be produced from this film. In addition, color positive transparencies can be made.

**Aerocolor HS film (Type SO-358)** is an extremely fine-grain, high-speed color negative aerial film designed specifically for low-altitude aerial photography. This film provides lower contrast than is considered normal for aerial color films.

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1Much of the information presented in this section is based on technical data provided by the Eastman Kodak Company, Rochester, NY.
Aerochrome II MS film (2448) is a very fine-grain, medium-speed reversal aerial color film designed for low- to medium-altitude mapping and reconnaissance work. This film has been used for a number of forest health protection activities.
Aerochrome HS film (SO-359) is a fine-grain, high-speed color reversal aerial film intended for low- to medium-altitude aerial mapping and reconnaissance missions. This film has been evaluated for forest health protection activities, has an excellent color balance, and would work well for forest damage detection and assessment. This film has performance characteristics similar to the SO-397 color positive transparency film referred to frequently in this manual but which is no longer available.

6.6.3. Color Infrared Films

Color infrared (CIR) films (sometimes referred to false-color or camouflage detection films) are sensitive, not only to visible light, but also to the region of the EMS known as near-IR (to approximately 0.9 µm). Because vegetation is highly reflective in the near-IR region of the EMS (Figure 2.2), these films are of great interest in forest health protection. Several papers detailing the properties and applications of these films are available: Fritz (1967), Greer et al. (1990), and Klein (1982b).

There is some confusion regarding CIR photography and the measurement of heat waves. This has led to futile attempts to detect thermal patterns with this film. The IR record in a CIR photograph is not a measure of ambient temperature variation. Thermal photography cannot be done with IR sensitive films because they are not thermal or heat detectors, and are only sensitive to the near-IR region of the EMS.

6.6.3.1. Characteristics. CIR films also consist of three dye-forming layers; however, their sensitivity has been shifted (Figure 6.6). The yellow dye layer is sensitive to green light, the magenta dye layer to red light and the cyan dye layer to the near-IR region. All three layers are inherently sensitive to blue light. Therefore, to limit the exposure of each layer of color to only its intended dye region, CIR films are always exposed through a medium yellow (minus blue) filter, such as a Wratten 12 or Wratten 15 (G) filter.

The resulting colors on CIR film are markedly different when compared to colors perceived by the human eye or as seen on color film (Figure 6.6). Live green vegetation, which is considerably more reflective in the near-IR region than in the green region, appears in varying hues of pink, red, magenta and red-brown. Moreover, the range of reflectance values in the near-IR region for vegetation is greater than in the green region (Figure 6.7). This allows for easier differentiation of forest vegetation types. Conifers, for example, will typically appear darker on CIR film than deciduous broadleaf trees. Green grass has the highest IR reflectance, and appears as a pink hue on CIR film (Figure 6.8).

Red colored objects typically appear as a yellow hue on CIR film. According to Figure 6.6, red-colored objects should appear as a green hue. This would be the case if a red colored object reflected only red light. Most red colored objects also reflect in the near-IR region, resulting in a yellow color on CIR film. True green hues are actually quite rare on CIR film. Water, which absorbs near-IR radiation, is typically black or dark blue on CIR film, and the contrast between water and land is much greater on a CIR photograph than on a color photo. As the level of sedimentation increases in lakes and streams, they appear in progressively lighter hues of blue.
Figure 6.6. Color reproduction on CIR films (sources, Eastman Kodak 1994, Fritz 1967).
## Figure 6.7. Comparison of colors seen on color and CIR films.

<table>
<thead>
<tr>
<th>COLOR IR</th>
<th>NATURAL COLOR</th>
<th>EXAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Healthy conifers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Healthy broadleaf vegetation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Grass, chlorotic foliage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Acutely chlorotic foliage, yellow fall coloring</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cured grasses, meadows and rangelands</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Conifers in the early stages of fading, dying broadleaf vegetation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Red flowers, dying conifer and broadleaf vegetation, red roofs, red fall coloring</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dead trees with a trace of red brown foliage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dead trees, foliar injury, defoliation caused by insects</td>
<td></td>
</tr>
</tbody>
</table>
A detailed discussion of the response of both color and CIR film to healthy vegetation and vegetation under varying degrees of stress is given by Murtha et al. (1997).

6.6.3.2. Historical Perspective. CIR film was originally developed in approximately 1942 for a military application: camouflage detection by aerial photography, and one of the first designations for this film was “Camouflage Detection film.” CIR film was sometimes effective when used to photograph objects such as tanks or anti-aircraft guns painted to appear like green foliage. Early camouflage paints, unlike green vegetation, did not reflect in the near-IR region and appeared as a blue color, whereas green vegetation appeared in varying hues of red or magenta (Figure 6.9). (More recently, green paints have been developed that do reflect in the near-IR region, and objects painted with an IR reflecting green paint will blend in with green vegetation when photographed with both color and CIR films.)

6.6.3.3. Uses in the Natural Resource Sciences. CIR film has been of great interest in forestry, pollution monitoring, hydrology, and related fields. A key reason for using CIR film is haze penetration. Most light scattering seen by the human eye as haze occurs in the blue region of visible light. Use of a CIR film with a minus-blue filter penetrates atmospheric haze caused by water vapor (but not smoke or cloud cover), often resulting in significantly clearer images than can be obtained with color film (Figure 6.10). Because many types of vegetation have greater differences in reflection in the near-IR region than they do in the visible green region of the EMS (Figure 6.8; Fritz 1967), they are more easily differentiated on CIR photographs.
6.6.3.4. **Pre-visual Detection of Plant Stress with CIR Film** - When CIR film first became available for civilian applications, there was a great deal of interest on the part of plant physiologists, pathologists, and others on its use for “pre-visual” detection of stress or disease. The theoretical basis for pre-visual detection of stress on IR films is discussed in detail by Murtha (1978). One of the first effects of plant stress was hypothesized to be a change in the level of near-IR reflectance, something that might be resolved on a near-IR sensitive film but not visible to the human eye. While there is some evidence of pre-visual stress detection in plants under laboratory conditions (Bawden 1933, Lillesand et al. 1975), there has been no repeatable aerial photographic evidence of pre-visual damage detection using visual PI techniques (Murtha 1978).

The ability to detect pines infested by southern pine beetle on CIR film before crown fading occurs was evaluated in 1965. This work showed that visual interpretation of CIR photographs of southern pine beetle spots at a scale of 1:4,000 could not discriminate between infested trees with green crowns and uninfested trees (Ciesla et al. 1967). Some studies have shown, however, that use of micro-densitometers to quantitatively assess the density of the blue, green, and red dye layers of exposed CIR film will sometimes show differences in exposure indicative of plant stress (Lillesand et al. 1978, Murtha 1978).
6.6.3.5. Film Types. Several CIR films are available for aerial photography. **Aerochrome Infrared Film (Type 2443)** is the standard CIR aerial film for photography missions at low to medium altitudes. This is a positive transparency (reversal) film. Some workers have developed a technique for processing this film to a negative and producing paper prints. However, this can cause significant changes in color balance and resolution. **Aerochrome Infrared NP film (SO-134)** and **Aerochrome Infrared Thin Base Film (SO-060)** are similar in film speed and processing to 2443 film but feature an increased IR sensitivity. They are designed for exposures at flight altitudes over 15,000 feet AGL where greater IR response is required. SO-060 thin base film is specifically designed for use with high-altitude reconnaissance camera systems (chapter 6, section 6.3.3).
In chapter 7, frequent reference is made to a CIR film designated as SO-131. This was the film used in conjunction with high-altitude panoramic aerial photography missions during the late 1970s and 1980s. Unfortunately, this product was discontinued because of manufacturing problems and was replaced by the two high-altitude films mentioned in the preceding paragraph. The two new products have not been evaluated for ability to resolve forest damage or other signatures of interest in forest health protection.

### 6.6.4. Color versus CIR Film

The selection of color or CIR film is one of the most critical decisions that a forest health specialist must make with regard to planning an aerial photography mission. Both films possess desirable attributes and, depending on the specific objectives of the photography mission, one film type may be superior to the other. Time permitting, 35-mm photographs with both CIR and color film can be taken over portions of the target area\(^2\). These can be studied by prospective photointerpreters to determine which film does the best job of resolving the signatures of interest.

As a general rule, there is nothing that can be seen on CIR film that cannot be seen by the naked eye or on color film. However, the false color nature of CIR film will often create a greater contrast between trees with symptoms of damage and healthy trees than can be seen with the naked eye or on color film. This is especially true with insect-caused defoliation, which typically appears as a gray hue on CIR film and a gray-brown on color film (Figure 6.11). The contrast of gray against a backdrop of red-colored healthy vegetation is much greater than gray-brown against a green backdrop. Add this feature to the ability of CIR film to more readily differentiate vegetation types and (in combination with a minus-blue filter) to penetrate haze, and this becomes an attractive alternative to color films for many forest health applications. A definite drawback of this film occurs when several damage types must be differentiated on the basis of subtle color differences. An excellent example is the presence of several species of coniferous bark beetles on different hosts in the western U.S., all of which have subtle differences in the color of fading crowns (chapter 3, section 3.3.2.1). It is considerably more difficult to separate these on CIR film than on color film (Ciesla 1977).

\(^2\)The 35-mm CIR film, designated Kodak Ektachrome Professional Infrared (EIR) film, can be processed using the standard E-6 slide film processing chemistry provided that the film is processed in total darkness.
Figure 6.11. Color (top) and CIR photograph (bottom) taken over a mixed pine-deciduous broadleaf forest in Mississippi. Note the ability of the CIR film to discriminate between conifers (C) and broadleaf trees (B), especially in the mixed stands (M). Note also the difference in appearance of insect caused defoliation (D) in portions of the pine type on the two films (original photographic scale = 1:6,000).

Guidelines for selection of color versus CIR film for forest insect surveys using aerial photography were first summarized by Ciesla (1977). The following dichotomous key is a modification of these guidelines for forest health assessments and may be used as a general guide in photography mission planning:
6.7. **FILTERS**

Several filters are used in combination with aerial films to adjust color balance or spectral sensitivity. The use of a medium yellow (minus-blue) Wratten 12 or Wratten 15 filter in combination with CIR film has already been discussed (chapter 6, section 6.6.3.1). A minus-blue filter is also standard equipment for use with panchromatic (black-and-white) aerial films for haze penetration.

It is possible to compensate for enhanced or degraded IR balance on CIR film by using various color-compensating filters and exposure-compensation changes (Moore 1980). In addition, color balance toward the blue, which can result from exposure of CIR film at high altitudes, where there is increased atmospheric attenuation of light, can also be corrected with filters (Fleming 1980).

If color film is to be exposed in an aerial camera that has been previously used for CIR or black-and-white film, it is important to check the camera lens to see if it contains a yellow filter. Failure to do this will result in color aerial photographs with a yellow cast, rendering them worthless for photointerpretation. While it is possible to correct the color balance of prints made from color-negative films if this mistake is made, no such correction can be made for color-positive transparency films.

Haze penetration or color correction filters (HF-2, 3, or 4) are sometimes used in conjunction with color aerial films to adjust for the overall blue cast resulting from high levels of atmospheric haze.

6.8. **PHOTOGRAPHY MISSION PLANNING**

Photography missions must be carefully planned in order to meet the objectives for which they are conducted. Some key factors to be considered in aerial photography mission planning include:

1. Camera format (section 6.3)
2. Lens focal length (section 6.4)
3. Scale (section 6.5.2)
4. Film type (section 6.6)
5. Is photographic point sampling (e.g., stereo triplets at predetermined intervals) or continuous photographic coverage over large blocks required?

### 6.8.1. Sampling with Aerial Photographs

The normal procedure for acquisition of photographic point-samples is to take them at more or less regular intervals along evenly spaced flight lines. The procedure for determining flight line and photograph interval along the flight lines is determined from the following relationship (USDA Forest Service n.d., White et al. 1983):

\[
I = \sqrt{\frac{A}{N}}
\]

where:

- \( I \) = Flight line interval and photographic point-interval along flight lines in miles
- \( A \) = Total area to be surveyed in square miles.
- \( N \) = Number of photographic sample points (photo plots).

**Example Exercise A:** An area of 250,000 acres is to be surveyed using stereo triplets at 30 sample points evenly distributed over the area. Determine the flight line interval and photographic point interval along the flight lines.

**Step 1:** Calculate the survey area in square miles.

\[
\text{250,000 acres/640 acres per square mile} = 390.63 \text{ miles}^2
\]

**Step 2:** Calculate the sample-point interval.

\[
I = \sqrt{\frac{390.63}{30}} = \sqrt{13.02} = 3.61 \text{ miles}
\]

The interval between photographs at each sample point is a function of the photographic scale and the desired overlap.

**Example Exercise B:** A series of stereo triplets with 60 percent overlap per photograph are to be acquired over a survey area with a 9-inch aerial camera equipped with an 8.25 inch focal length lens at a scale of 1:8,000. Determine flying height AGL and photograph interval.

**Step 1:** Determine flying height AGL.

\[
\begin{align*}
8.25 \text{ in./12 in./ft.} &= 0.6875 \text{ ft.} \\
1:8,000 &= 0.6875 \text{ ft.} \times x \text{ ft.} \\
x &= 8,000 \times 0.6875 \text{ ft.} \\
x &= 5,550 \text{ ft} \text{ above mean terrain elevation (MTE)}
\end{align*}
\]
Step 2: Determine interval between photographs.

First, convert film format dimension from inches to feet.

\[ \frac{9 \text{ in.}}{12 \text{ in.}} = 0.75 \text{ ft.} \]

Next, multiply the film dimension by the scale to yield coverage.

\[ \text{In-tract distance with no overlap} = 0.75 \times 8,000 = 6,000 \text{ ft.} \]

Finally, calculate the photographic point interval.

\[ \text{specified overlap} = 60 \text{ percent, so} \]
\[ \text{the point interval} = 6,000 \text{ ft.} \times (1-.60) \]
\[ = 2,400 \text{ ft.} \]

6.8.2. Aerial Photography of Small Blocks

In some instances, it may be necessary to acquire standard mapping-type aerial photograph coverage with overlap and sidelap. This requires computation of the distance between flight lines, the photographic point interval along the flight line and the total number of photographs to be taken. A five-step process for making these computations is outlined as follows:

Example Exercise: - A 9-inch camera, equipped with an 8.25 inch focal length lens, is to be used to acquire 1:8,000 scale mapping photography with 60 percent overlap and 30 percent sidelap over a quarter section of a USGS 7.5 minute map. Block dimensions are 3.25 miles wide by 4.2 miles long. Use this information to determine:

1. Flight line interval
2. Number of flight lines
3. Photo point interval along flight lines
4. Total number of photographs

Step 1: Determine flying height AGL.

Using the formula in section 6.7.1, Example Exercise B, Step 1, flying height AGL is calculated at 5,500 ft.
**Step 2:** Determine interval between flight lines.

First, convert film format dimension from inches to feet.

\[ \frac{9 \text{ in.}}{12 \text{ in./ft.}} = 0.75 \text{ ft.} \]

Next, multiply the film dimension by the scale to yield the coverage.

Flight line interval with no sidelp = \( 0.75 \times 8,000 = 6,000 \) ft.

Finally, calculate the interval.

The specified sidelp = 30 percent, so the **flight line interval** = \( 6,000 \times (1-0.30) = 4,200 \) ft.

**Step 3:** Determine the number of flight lines.

Block width = \( 3.25 \text{ miles} \times 5,280 \text{ ft./mile} = 17,160 \) feet

\( \frac{17,160 \text{ ft.}}{4,200 \text{ ft.}} = 4.08 \text{ or 4 flight lines} \)

**Step 4:** Determine photographic point interval along a flight line.

In tract distance with no overlap = \( 0.75 \times 8,000 = 6000 \) ft.

The specified overlap = 60 percent, so the **photographic point interval** = \( 6,000 \times (1-0.60) = 2,400 \) ft.

**Note:** This is the same computation made in section 6.7.1, Example Exercise 2, Step 2.

**Step 5:** Determine number of photographs on a flight line.

Block length = \( 4.2 \text{ miles} \times 5,280 \text{ ft./mile} = 22,176 \) feet

\( \frac{22,176 \text{ feet}}{2,400 \text{ feet between photographs}} = 9.24 \text{ or 10 photographs per flight line} \)

**Step 6:** Determine total number of photographs required

4 flight lines \( \times \) 10 photographs/flight line = **40 photographs**
6.9. **PHOTOINTERPRETATION**

Photointerpretation (PI) is the process of taking data from the aerial photographs. This operation can range from making precise measurements of distances for production of maps to classification of anything from vegetation types or geological formations to the number and types of military aircraft parked on an airstrip of an unfriendly nation. In forest health protection, as discussed previously in chapter 4, section 4.2.1, photointerpretation typically involves two operations: **classification** (stratification of various vegetation types or damage classes) and **enumeration** (making counts of dead, dying, or symptomatic trees). Depending on the nature of the signatures of interest, classification can be done either by viewing aerial photographs monoscopically or stereoscopically. Counts of individual trees are generally done with the aid of mirror stereoscopes and a light table (Figure 6.12).

![Figure 6.12. A photointerpreter classifying or enumerating forest damage with the aid of a mirror stereoscope.](image)

6.9.1. **Photointerpretation Standards**

As is the case in aerial sketchmapping, a critical part of photointerpretation is the development of standards to ensure that all persons engaged in a PI project are making the same classifications or counting trees with the established attribute(s) of interest. PI standards can be relatively simple, such as producing a brief written description of the attribute of interest. For example, for PI of defoliation of broadleaf forests by gypsy moth in the mid-Atlantic States, the following classification standards used by the Pennsylvania Bureau of Forestry for aerial sketchmapping were also used to classify defoliation on high-altitude panoramic aerial photographs (Ciesla and Acciavatti 1982):

- **No aerially visible defoliation.**
• **Moderate and Widespread.** Pure host type with first noticeable defoliation visible from aerial observation—generally, 30 to 60 percent defoliation.

• **Heavy and Widespread.** Pure host type with total loss of host foliage—generally, greater than 60 percent defoliation.

In cases where trees with a number of different damage types must be classified and/or enumerated, or there is a probability of trees with other attributes in the scene that could be sources of commission error, it may be necessary to develop a PI key to aid photointerpreters. PI keys can take on several forms. They may consist of simple drawings that describe the signatures of objects that should be classified and possible sources of commission error, narrative descriptions of the various signatures of interest, a dichotomous key, or various combinations of these (Figures 6.13 and 6.14). If the PI project is especially complex, such as one that requires several stages of PI (e.g., multistage classification of vegetation types, damage classes, and counts of symptomatic trees) it may be necessary to develop a manual of PI standards, complete with illustrations, PI keys, and forms for data recording (Ciesla 1984b).

An important aspect of PI is to train photointerpreters on the project requirements so that there is a common understanding of the data to be collected and the signatures of the objects that are to be classified and/or enumerated. A useful approach is to have two photointerpreters (e.g., one experienced and one trainee) view the same segment of an aerial photograph with either a pair of stereoscopes or with a mirror stereoscope designed for dual viewing. This approach allows the two photointerpreters to study and discuss the signatures they are viewing and will, hopefully, result in consistent interpretation with a minimum of error (Figure 6.15).
Figure 6.13. Pictorial key to aid photointerpreters in classification of hardwood forest damage in Vermont: A. An apparently healthy hardwood, B. A slightly chlorotic hardwood (trees that fall into this class have a full complement of foliage with a yellow-green color. On CIR, such trees have a pink hue, C. An acutely chlorotic hardwood. These trees have foliage with a distinct yellow color, and appear white on CIR film, D. Hardwood with a full complement of healthy foliage and “flags” of acutely chlorotic or dying foliage (this is a signature characteristic of the early stages of Dutch elm disease). E. Hardwood with branch dieback in crown. Color of living foliage may be indicative of a healthy crown, slight chlorosis, or early fall coloring. Foliage may also have a thin appearance. F. Recently dead hardwood. Crown has a dendritic network of many fine branches, G. Older dead hardwood with fewer fine branches, H. Recently dead conifer with many fine branches radiating from mainstem. I. Snag with only mainstem or 1-2 lateral branches remaining (redrawn from Ciesla et al. 1985).
Figure 6.14. Dichotomous key designed to aid photointerpreters in classification of areas in Vermont affected by hardwood decline and mortality (For photographs taken from August to early September) (Ciesla et al. 1985).

1. Little or no foliage present, bare branches visible ............................................ Go to 2..
   1a. Foliage present in at least part of crown ...................................................... Go to 5..

2. Branch pattern dendritic, color light gray or white (dead hardwood) ............ Go to 3..
   2a. Branches radiating from a central mainstem color light gray or white..... Dead conifer.

3. Fine branches abundant, color light gray or blue gray.............. Recent dead hardwood.
   3a. Fine branches less abundant or entirely missing, color white ....................... Go to 4..

4. Some fine branches still present ................................................................. Older dead hardwood.
   4a. Only mainstem or one or two large lateral branches present .................. Snag.

5. Foliage color red, magenta or red brown ..................................................... Go to 6..
   5a. Foliage color pink, white, yellow or red-orange ........................................... Go to 9..

6. Crown conical or deeply lobed, foliage color normally dark red-brown or red-violet (light red brown near sunspot) ................................................. Living conifer.
   6a. Crown rounded, wide-spreading, foliage color red, light reddish brown or magenta ... Go to 7..

7. Foliage color light reddish brown ................................................................. Foliage injury by leaf mining or skeletonizing insects.
   7a. Foliage color red or magenta ................................................................. Go to 8..

8. Dead branches visible in crown .................. Hardwood with top or branch dieback.
   8a. Dead branches not visible in crown .................................. Apparently healthy hardwood.

9. Foliage color yellow or orange-yellow .......................................................... Go to 11..
   9a. Foliage color white or pink ................................................................. Go to 12..

10. Foliage color a distinct yellow .............................................................. Hardwood with premature fall coloring.
10a. Foliage color yellow-orange or orange ........ Hardwood with premature fall coloring.

11. Crown shape conical .......................................................... Dying conifer (Spruce or fir).

12. Foliage color pink ............................................................... Slightly chlorotic hardwood.
12a. Foliage color white ............................................................... Acutely chlorotic hardwood.
6.9.2. Photointerpretation Aids

The primary PI aid developed for forest health assessments with aerial photographs is a clear plastic equal area grid overlay. This allows the photointerpreter to classify trees on a sample of known size on an aerial photograph (White et al. 1983). Equal area grids can vary by the number of cells to be classified and the area of individual cells depending on the data collection requirements. The dimensions of an individual cell on an equal area grid overlay will vary by the area to be classified and photographic scale, and can be computed as follows:

**Example Exercise:** Determine the dimensions of a series of 2.5-acre equal-area grid cells at a photographic scale of 1:8,000.

**Step 1:** Compute the ground dimensions of a 2.5-acre-square block.

\[
\begin{align*}
\text{If 1 acre} & = 43,560 \text{ ft.}^2, \text{ then} \\
2.5 \times 43,560 & = 108,900 \text{ ft.}^2, \text{ and} \\
\sqrt{108,900} & = 330 \text{ feet}
\end{align*}
\]
Step 2: Compute the cell dimensions at the given photographic scale.

\[
1:8,000 = 1 \text{ ft.} = 8,000 \text{ feet or } 12 \text{ in.} = 8,000 \text{ ft.}
\]
\[
12 \text{ in./8000 ft.} = \frac{x}{330 \text{ ft.}}
\]
\[
x = \frac{(330 \cdot 12)}{8,000}
\]
\[
x = 0.495 \text{ inches}
\]

Because some variation in photographic scale can be expected during an aerial photography mission, especially over mountainous terrain, it is a good practice to generate equal area grid cell overlays in a range of scales either side of the targeted photographic scale. The actual scale of each photographic pair or triplet on which a grid is to be overlaid is determined using the procedure outlined in chapter 6, section 6.5.1. The grid cell overlay that most closely matches the actual photographic scale is then used. Grid cell overlays in scale unit increments of 250 feet are generally sufficient for photographic scales in the range of 1:4,000 to 1:10,000 and can be easily computed by entering the range of scales and the formula given in Step 2 of this section into spreadsheet software such as Microsoft Excel, Lotus 1-2-3, or Corel Quattro Pro (Table 6.2).

Table 6.2. Dimensions of 2.5 acre equal area grid cells for photographic scales ranging from 1:7,000 to 1:9,000 (target photography mission scale = 1:8,000).

<table>
<thead>
<tr>
<th>Photographic Scale</th>
<th>Dimensions of a Square 2.5-Acre Grid Cell (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:7,000</td>
<td>0.566</td>
</tr>
<tr>
<td>1:7,250</td>
<td>0.546</td>
</tr>
<tr>
<td>1:7,500</td>
<td>0.528</td>
</tr>
<tr>
<td>1:7,750</td>
<td>0.523</td>
</tr>
<tr>
<td>1:8,000</td>
<td>0.495</td>
</tr>
<tr>
<td>1:8,250</td>
<td>0.480</td>
</tr>
<tr>
<td>1:8,500</td>
<td>0.466</td>
</tr>
<tr>
<td>1:8,750</td>
<td>0.453</td>
</tr>
<tr>
<td>1:9,000</td>
<td>0.440</td>
</tr>
</tbody>
</table>

The actual grid cell overlays can be either hand drafted using the computed dimensions or computer-generated. A simple way of generating precise grid cell overlays for PI is via the table generation routine in word processing software, such as Corel WordPerfect. Simply create a table using the row- and column-generating functions to create the desired number of cells. An extra column and row may be generated for entry of row and column identifiers. Using the table format command, set the row and column widths as computed in Step 2 of the computation described in this section. Print the resulting (empty) table onto a transparency sheet. Repeat this procedure until the complete range of grid cells is generated (Figure 6.16).
Figure 6.16. Equal area grid cell consisting of 100 - 2.5 acre cells at a photographic scale of 1:8,000.

Other PI aids of interest in forest health assessment include **dot grids** for estimating area, and **crown closure scales** and **crown diameter scales** for describing stand conditions for stand hazard rating maps (Figure 6.17). These are available from engineering or forestry equipment suppliers.
Figure 6.17. A clear plastic photointerpreter’s scale with three parts. **Left** - Crown closure and crown diameter scale. **Upper right** – Equal-area grid. **Lower right** - Dot grid for estimating area. (Developed by University of Michigan, School of Natural Resources.)
6.10. ANALYSIS OF DATA FROM AERIAL PHOTOGRAPHIC SURVEYS

Surveys using aerial photographs or a combination of aerial photographs and ground surveys in multistage inventory designs can be analyzed and displayed in many ways. The following sections describe, in a step by step manner, two analytical procedures: **double-sampling with regression** and **probability proportional to size sampling**.

6.10.1. Double-Sampling with Regression

Double-sampling with regression, a relatively simple approach for combining data from remote sensing and ground information to estimate the amount of tree mortality and/or volume affected, is described in detail by Wear et al. (1966). This method employs two stages, or a stage within a stage. The first stage consists of a large sample acquired via remote sensing (e.g., aerial photograph plots) in which counts of the attribute of interest, such as the number of dead trees, is made. The second stage consists of a sub-sample of these plots, which are visited on the ground and the number of dead trees and/or their volume is measured. The photograph and field data for the second stage provides the basis for computing a linear regression that expresses the relationship between the photographic and field counts. The final estimate of the amount of damage is obtained by using the regression to adjust the data from the first stage. This method has been used to estimate tree mortality caused by bark beetles in the western United States (Dolph and Wear 1963, Ciesla et al. 1971b, Wear et al. 1966).

The following example of the double-sampling with regression analysis procedure is taken from an inventory of tree mortality caused by the Douglas fir beetle in the North Fork Clearwater River drainage in northern Idaho in 1971 (Ciesla et al. 1971b; chapter 7, section 7.1.1.2) as described by Freese (1967) and Wear et al. (1966). In this inventory, some 288,000 acres of federal, state, and private lands were affected, 100 aerial photograph plots of 100 acres each were established in the survey area, and the number of fading Douglas-fir were counted. Twenty-six of these plots were selected for field measurements. The example shown is for estimating the number of trees killed in 1970. The data for the photographic counts from the large photograph sample is shown in table 6.3 and the data for the photograph and field counts from the second stage is shown in table 6.4.

**Step 1:** Mean photographic count, large sample.

The mean photographic count of the large photographic sample is determined by the formula:

\[
\bar{x}_1 = \frac{\sum x_1}{n_1}
\]

where:

- \(\bar{x}_1\) = mean count of large photographic sample
- \(x_1\) = count of dead trees on a plot in the large photographic sample
- \(n_1\) = number of plots in the large photographic sample

Using the data in table 6.3:
\[ 391 + 335 + 155 + 106 = 987 \]

\[ \bar{x}_1 = \frac{987}{100} = 9.87 \text{ fading Douglas-fir per plot} \]

Table 6.3. Photographic counts of fading Douglas-fir on 100 100-acre photographic plots, North Fork, Clearwater River, Idaho, 1971 (Ciesla et al. 1971b).

<table>
<thead>
<tr>
<th>Plot</th>
<th>Trees</th>
<th>Plot</th>
<th>Trees</th>
<th>Plot</th>
<th>Trees</th>
<th>Plot</th>
<th>Trees</th>
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<td>0</td>
<td>74</td>
<td>5</td>
<td>99</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>75</td>
<td>24</td>
<td>100</td>
<td>32</td>
</tr>
<tr>
<td>Totals</td>
<td>391</td>
<td>335</td>
<td>155</td>
<td>106</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6.4. Photo and field counts of numbers of fading Douglas-fir and regression equation computations, North Fork, Clearwater River, Idaho, 1971 (Ciesla et al. 1971b).

<table>
<thead>
<tr>
<th>Plot number</th>
<th>Photographic Count (x)</th>
<th>Field Count (y) (trees killed in 1970)</th>
<th>$x^2$</th>
<th>$y^2$</th>
<th>xy</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>30</td>
<td>33</td>
<td>900</td>
<td>1,089</td>
<td>990</td>
</tr>
<tr>
<td>11</td>
<td>9</td>
<td>72</td>
<td>81</td>
<td>5,184</td>
<td>648</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>15</td>
<td>121</td>
<td>225</td>
<td>165</td>
</tr>
<tr>
<td>14</td>
<td>20</td>
<td>0</td>
<td>400</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>2</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>21</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>23</td>
<td>0</td>
<td>36</td>
<td>0</td>
<td>1,296</td>
<td>0</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>27</td>
<td>217</td>
<td>258</td>
<td>47,089</td>
<td>66,564</td>
<td>55,986</td>
</tr>
<tr>
<td>28</td>
<td>4</td>
<td>0</td>
<td>16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>29</td>
<td>25</td>
<td>79</td>
<td>625</td>
<td>6,241</td>
<td>1,975</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>35</td>
<td>5</td>
<td>84</td>
<td>25</td>
<td>7,056</td>
<td>420</td>
</tr>
<tr>
<td>37</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>38</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>39</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>51</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>53</td>
<td>15</td>
<td>160</td>
<td>225</td>
<td>25,600</td>
<td>2,400</td>
</tr>
<tr>
<td>55</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>57</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>63</td>
<td>7</td>
<td>0</td>
<td>49</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>66</td>
<td>22</td>
<td>59</td>
<td>484</td>
<td>3,481</td>
<td>1,298</td>
</tr>
<tr>
<td>68</td>
<td>4</td>
<td>0</td>
<td>16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Totals</td>
<td>374</td>
<td>818</td>
<td>50,038</td>
<td>117,220</td>
<td>63,882</td>
</tr>
<tr>
<td>Averages</td>
<td>14.38</td>
<td>31.46</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Step 2. Regression of field counts over photographic counts for the second stage.

Using data in table 6.4, the following calculations are made to compute the linear regression of the field counts over the photographic counts:

1. The mean photographic count on the small sample:

\[
\bar{x}_2 = \frac{\sum x_2}{n_2} = \frac{374}{26} = 14.38 \text{ fading Douglas-fir/plot.}
\]

where:

- \(x_2\) = mean photographic count of the small photographic sample
- \(x_2\) = interpreter’s count of dead trees on a plot in the small photographic sample
- \(n_2\) = number of plots in the small photographic sample

2. The mean field count on the small sample:

\[
\bar{y}_2 = \frac{\sum y_2}{n_2} = \frac{818}{26} = 31.48 \text{ Douglas-fir killed/plot in 1970}
\]

3. The corrected sum of squares for x:

\[
\sum x^2 = \sum x^2 - (\sum x)^2/n_2 = 50,038 - (374)^2/26 = 44,658.15
\]

4. The corrected sum of squares for y:

\[
\sum y^2 = \sum y^2 - (\sum y)^2/n_2 = 117220 - (818)^2/26 = 91,484.6
\]

5. The corrected sum of the cross products:

\[
\sum xy = \sum (xy) - (\sum x)(\sum y)/n_2 = 63882 - (374)(818)/26 = 52,115.38
\]

6. The regression coefficient of y on x (slope):

\[
b = \frac{\sum xy}{\sum x^2} = \frac{52115.38}{44685.15} = 1.17
\]

7. The y-intercept (a):

\[
a = \bar{y}_2 + b\bar{x}_2 = 31.46 - (1.17)(14.36) = 14.66
\]

Therefore, the linear regression equation for the relationship between photographic counts and tree counts (Figure 6.18) is:

\[
y = 14.67 + 1.17x
\]
Step 3. Significance of the Regression.

A test of how well the regression line fits the data can be made using an F-test (Freese 1967) as follows:

Reduction sum of squares (SS) = \( \frac{(\sum xy)^2}{\sum x^2} = \frac{(52115.38)(52115.38)}{44658.15} = 60,817.86 \)

Residual SS = \( \sum y^2 - \text{Reduction SS} = 91484.46 - 60817.86 = 30,666.60 \)

Using these values, an analysis of variance table is developed (Table 6.5).
Table 6.5. Analysis of variance table to test significance of the regression of photographic counts versus field counts, North Fork Clearwater River Drainage, Idaho, 1971 (Ciesla et al. 1971b).

<table>
<thead>
<tr>
<th>Source of Variation</th>
<th>Degrees of Freedom (DF)</th>
<th>Sum of Squares (SS)</th>
<th>Mean Squares (MS) ( = SS/DF)</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Due to regression</td>
<td>1</td>
<td>60,817.86</td>
<td>60,817.86</td>
<td>47.60</td>
</tr>
<tr>
<td>Residual (unexplained)</td>
<td>24</td>
<td>30,666.60</td>
<td>12,77.78</td>
<td></td>
</tr>
<tr>
<td>Total ( =∑y²)</td>
<td>( = n² - 1) 25</td>
<td>91,484.46</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

An F-test is computed as follows:

\[ F = \frac{\text{Regression mean squares (MS)}}{\text{Residual MS}} = \frac{60,817.86}{1,277.78} = 47.60 \]

Using a standard “F” table (Freese 1967), the computed value of 47.60 is greater than 7.82 at 1 and 24 degrees of freedom (DF); therefore, the regression is significant at the 99-percent level.

**Step 4.** Coefficient of Determination (R²).

The coefficient of determination (R²) is a measure of how well the regression fits the data, and is based on the total variation in Y that is associated with the regression. R² is computed as follows:

\[ R^2 = \frac{\text{Reduction SS}}{\text{Total SS}} = \frac{60,817.86}{91,484.15} = 0.665 \]

**Step 5.** Estimated number of trees.

The number of trees per plot is estimated from the combined photographic and field plot data using the relationship:

\[ \hat{y}_{id} = \hat{y}_2 + b (\bar{x}_1 - \bar{x}_2) \]
\[ = 31.46 - (1.17)(9.87-14.38) \]
\[ = 26.18 \text{ fading Douglas-fir/100-acre plot} \]

\[ 26.18/100 = 0.2618 \text{ fading Douglas-fir/acre} \]

\[ 0.2618 \cdot 288,000 = \textbf{75,398.4 fading Douglas-fir} \text{ over the survey area} \]

**Step 6.** Sampling error.

1. The corrected sums of squares for y (∑y²) from step 2 - 4 = 91,484.6

2. The variance of y (Sy²) = \( S_y^2 = \sum y^2 / (n^2 - 1) \) = 91484.6/25 = 3,659.38
3. The variance for the regression:

\[ \text{Sy.x}^2 = \frac{(\sum y^2 - (\sum xy)^2)}{(n^2 - 2)} \]
\[ = \frac{(91484.6 - 60817.85)}{24} \]
\[ = 1,277.78 \]

4. The sampling error (S_{yd}):

\[ S_{yd} = \sqrt{(\text{Sy.x}^2) \cdot \left( \frac{1}{n^2} \cdot \frac{(x_1 - x_2)^2}{\sum x^2} \cdot (1-(n^2/n_1)) + \frac{\sum y^2}{n_1} \right) + 3,659.38/100} \]
\[ = \sqrt{1277.8 \cdot (1/26 \cdot ((9.78-14.38)/44658.15) \cdot (1-(26/100)) + 3,659.38/100} \]
\[ = 8.53 \text{ fading Douglas-fir per plot or 8.53/100} \]
\[ = 0.0853 \text{ fading Douglas-fir/acre} \]

5. The percentage sampling error:

\[ = \frac{0.0853}{S_{yd}} \]
\[ = 0.0853/0.2618 \]
\[ = 32.5 \text{ percent} \]

6. The sampling error for the total number of Douglas fir killed in 1970:

\[ = 75,398.4 \cdot 0.3258 = 24,564.8 \text{ or} \]
\[ = 75,398.4 \pm 24,564.8 \text{ trees} \]

6.10.2. Probability Proportional to Size Sampling

A probability proportional to size (PPS) sampling procedure was developed for aerial photo/ground inventories of losses caused by the mountain pine beetle and is described in detail by White et al. (1983). This procedure provides estimates of tree mortality and related volume loss over a large area (e.g., a state, region, or forest) with a prescribed level of precision. The survey is a multi-stage, single-phase design based on a combination of stratification and multi-phase probability sampling, and can be applied to any situation where estimates of mortality caused by a single causal agent are required.

Tree mortality is sampled by random selection of aerial photograph plots for ground sampling. A photointerpretation sampling grid, subdivided into subplots is the primary sampling unit (PSU). Subplots of 2.5 acres are the secondary sampling unit (SSU). Primary and secondary sampling units are selected following the PPS technique with replacement.
The following example illustrates the data analysis for this type of survey:

**Example Exercise:** A survey of tree mortality is made over 100,000 acres of ponderosa pine forest infested by mountain pine beetle in Colorado. **Fifty 90-acre** photographic plots are established in a single stratum within the outbreak area. **Two 2.5-acre** subplots are ground checked on each of 10 photographic plots, for which a total of 2,000 faders have been recorded by photointerpreters. Data recorded on the ground subplots include number of trees killed and volume affected in ft$^3$ (Table 6.6).

The sampling parameters for this survey are:

1. Acres of outbreak (A) = 100,000 acres
2. Photographic sample size (a) = 90 acres
3. Total number of photographic plots (m) = 50
4. Number of photographic samples (n) = 10
5. Accumulated PI count (PC) = 2,000 trees

Table 6.6. Summary of PI and ground data for an inventory of mountain pine beetle losses over an outbreak area in Colorado (White et al. 1983).

<table>
<thead>
<tr>
<th>Photo Plot</th>
<th>Total Photo Plot PI Count (faders)</th>
<th>PI Count (faders)</th>
<th>Ground Data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Subplot 1</td>
<td>Subplot 2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(trees) (5)</td>
<td>(trees) (7)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(volume -ft$^3$)</td>
<td>(volume -ft$^3$)</td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>15</td>
<td>20</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>250</td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>25</td>
<td>30</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>27</td>
<td>300</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>30</td>
<td>750</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>33</td>
<td>100</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>37</td>
<td>250</td>
<td>20</td>
<td>6</td>
</tr>
<tr>
<td>42</td>
<td>100</td>
<td>25</td>
<td>15</td>
</tr>
<tr>
<td>46</td>
<td>100</td>
<td>10</td>
<td>15</td>
</tr>
</tbody>
</table>

Data recorded on the ground subplots include number of trees killed and volume affected in ft$^3$.
Note: In this hypothetical example, all trees were assigned a volume of 15 ft³/tree to simplify computations. Since there was no variation in tree volume, relative SE for trees and volume is identical. This will not occur with actual field data.

The estimated number of trees killed and associated volume loss is computed as follows:

**Step 1.** Estimated number of trees killed and standard error.

- Sum of expanded trees = \( \sum \text{column 18 (table 6.7.)} = \sum \hat{y} \text{ trees} = 21,162.34 \)

- Sum of squares (trees) = \( \sum \hat{y}^2 \text{ trees} = 44,966,408 \)

Tree estimates:

\[
\text{Total trees} = \left( \frac{A}{(a)(m)} \right) \cdot \left( \frac{\sum \hat{y} \text{ trees}}{n} \right)
\]

\[
= (100,000)/(90)(50) \cdot \left( \frac{21,162.34}{10} \right)
\]

\[
= 46,980.39
\]

\[
\text{SE}_t = \sqrt{\left( \frac{A}{(a)(m)} \right)^2 \cdot \left( \frac{\sum \hat{y}^2 \text{ trees} - \left( \frac{\sum \hat{y} \text{ trees}}{n} \right)^2}{n(n-1)} \right)}
\]

\[
= \sqrt{\left( \frac{10,000}{(90)(50)} \right)^2 \cdot \left( \frac{44,966,408 - \left( \frac{447,844,634}{10} \right)/10}{9} \right)}
\]

\[
= 991.1
\]

\[
\% \text{ SE}_t = \left( \frac{\text{SE}_t}{\text{total trees}} \right) \cdot 100
\]

\[
= 999.1/46,980.39 \cdot 100
\]

\[
= 2.13 \text{ percent}
\]

**Step 2 -** Estimated volume affected and standard error.

- Sum of expanded volume = \( \sum \text{column 19 (table 4.x):} \)

\[
\sum \hat{y} \text{ volume} = 317,431.9
\]

- Sum of squares (volume):

\[
\sum \hat{y}^2 \text{ volume} = 10,117,246,050
\]

Volume estimates:

\[
\text{Total volume} = \left( \frac{A}{(a)(m)} \right) \cdot \left( \frac{\sum \hat{y} \text{ volume}}{n} \right)
\]

\[
= 100000/(90)(50) \cdot \left( \frac{317431.9}{10} \right)
\]

\[
= 704,699 \text{ ft}^3
\]
\[
SE_v = \sqrt{(A/(a(m))^2 \cdot ((\sum \hat{y}^2 \text{ volume} - ((\sum \hat{y} \text{ volume})^2 /n)/n(n-1)))}
\]
\[
= \sqrt{(10,000/((90)(500))^2 \cdot ((10,117,146,050) - ((100,763,011,100/10)/(10)(9)))}
\]
\[
= 14,988.39
\]

\%
\[
SE_v = (SE/\text{total volume}) \cdot 100
\]
\[
= 14,988.39/704,699 \cdot 100
\]
\[
= 2.13 \text{ percent}
\]

Estimates for total number of trees and volume for the total areas of a photographic plot are made on a worksheet specifically designed for this analysis (Table 6.7; White et al. 1983).
Table 6.7. Work sheet for plot estimates of trees and volumes inventory of mountain pine beetle losses over an outbreak area in Colorado (White et al. 1983).

<table>
<thead>
<tr>
<th>Subplot Expansions</th>
<th>Tree Expansions</th>
<th>Plot Estimate for Trees ((13) (((11) \cdot (12))/2))</th>
<th>Volume Expansions ((\text{ft}^3))</th>
<th>Plot Estimate for Volume ((16) (((14) \cdot (15))/2))</th>
<th>Photo Plot Expansions ((17) \text{PC}/(2))</th>
<th>Total Trees ((\hat{y} \text{ trees}))</th>
<th>Total Volume ((\hat{y} \text{ volume}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subplot-1 ((9) (2)/(3)^*)</td>
<td>Subplot-2 ((10) (2)/(4))</td>
<td>Subplot-1 ((11) (5) \cdot (9))</td>
<td>Subplot-2 ((12) (7) \cdot (10))</td>
<td>Subplot-1 ((14) (6) \cdot (9))</td>
<td>Subplot-2 ((15) (8) \cdot 10)</td>
<td>((13) \cdot \text{PC} \cdot (17))</td>
<td>((18) \cdot (19) \cdot (17))</td>
</tr>
<tr>
<td>20.0</td>
<td>5.0</td>
<td>120.0</td>
<td>105.0</td>
<td>112.5</td>
<td>1800.0</td>
<td>1575.0</td>
<td>1687.5</td>
</tr>
<tr>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>20.0</td>
<td>300.0</td>
<td>300.0</td>
<td>300.0</td>
</tr>
<tr>
<td>8.3</td>
<td>5.0</td>
<td>265.6</td>
<td>265.0</td>
<td>265.3</td>
<td>3984.0</td>
<td>3975.0</td>
<td>3979.5</td>
</tr>
<tr>
<td>30.0</td>
<td>15.0</td>
<td>30.0</td>
<td>30.0</td>
<td>30.0</td>
<td>450.0</td>
<td>450.0</td>
<td>450.0</td>
</tr>
<tr>
<td>15.0</td>
<td>20.0</td>
<td>315.0</td>
<td>320.0</td>
<td>317.5</td>
<td>4725.0</td>
<td>4800.0</td>
<td>4762.5</td>
</tr>
<tr>
<td>7.5</td>
<td>10.0</td>
<td>787.5</td>
<td>800.0</td>
<td>793.8</td>
<td>11812.5</td>
<td>12000.0</td>
<td>11906.25</td>
</tr>
<tr>
<td>20.0</td>
<td>20.0</td>
<td>100.0</td>
<td>100.0</td>
<td>100.0</td>
<td>1500.0</td>
<td>1500.0</td>
<td>1500.0</td>
</tr>
<tr>
<td>12.5</td>
<td>41.6</td>
<td>225.0</td>
<td>291.2</td>
<td>258.1</td>
<td>3871.5</td>
<td>4368.0</td>
<td>3871.5</td>
</tr>
<tr>
<td>4.0</td>
<td>6.7</td>
<td>112.0</td>
<td>133.4</td>
<td>122.7</td>
<td>1840.5</td>
<td>2001.0</td>
<td>1840.5</td>
</tr>
<tr>
<td>10.0</td>
<td>6.7</td>
<td>110.0</td>
<td>93.4</td>
<td>101.7</td>
<td>1525.4</td>
<td>1400.7</td>
<td>1525.35</td>
</tr>
</tbody>
</table>

*Numbers refer to column numbers in Table 6.6 and this table.
7. AERIAL PHOTOGRAPHY–APPLICATIONS

Aerial photography has been an operational tool for acquisition of data on forest damage since the mid 1960s. This chapter describes case histories of uses of aerial photography for acquisition of data in support of activities related to forest health protection both in Canada and the United States.

7.1. INVENTORIES

For purposes of this presentation, inventories are defined as forest health assessments that include, as part of their objectives, estimates of the number of trees affected and/or volume losses. The following sections describe uses of aerial photography for inventories of several species of tree-killing bark beetles, diebacks and declines, root disease defoliators, and dwarf mistletoe.

7.1.1. Bark Beetles

7.1.1.1. Southern Pine Beetle. A survey method using a combination of 9-inch CIR aerial photography and ground surveys was developed in the mid 1960s for assessment of outbreaks of the southern pine beetle (Ciesla et al. 1967). This inventory provides estimates of the number of infested areas (spots) and number of actively infested trees per 1,000 acres of host type (pine-pine/hardwood) using a statistical design developed for operation recorder surveys (Ketcham 1964).

Either an entire political unit (e.g., county, National Forest, etc.) was included in the survey or the general area of infestation was determined from aerial sketchmap surveys (Figure 4.3; USDA Forest Service n.d.). Aerial photographic plots were established over the general area of infestation on a systematic grid (minimum of 30 plots). A 9-inch CIR stereoscopic triplet was taken at each photographic plot location at a photographic scale of 1:4,000, 1:6,000, or 1:8,000. Photographic plots were 50 acres on the 1:4,000-scale photographs (4 by 5 inches) and 200 acres (4.5 by 7.44 inches or 4 by 5 inches) on the 1:6,000 and 1:8,000-scale photographs, respectively. The area of susceptible host type (pine-pine/hardwood) and number of active bark beetle spots was determined for each plot, and a photographic count of the number of trees in each spot was made. A sub-sample of photographic plots containing bark-beetle spots was randomly selected for ground examination, and counts of the number of actively infested trees per spot were made.

These inventories were conducted for several years across the southeastern U.S. but were eventually discontinued because of the relatively few cloud-free days during the summer months when aerial photography could be acquired.

7.1.1.2. Douglas-fir Beetle. Mortality caused by an outbreak of Douglas-fir beetle was assessed on 650,000 acres in northern California using a stratified sampling design with 9-inch 1:8,000-scale color aerial photographs (Wert and Roettgering 1968). This survey had a cost benefit ratio of 1:100 when compared to the cost of ground surveys required to obtain the same data at the same level of accuracy (12 percent sampling error).

In 1971, an outbreak of Douglas-fir beetle was detected on 288,000 acres of federal, state, and private lands in the North Fork Clearwater River drainage in northern Idaho. A multistage, aerial photographic ground survey with a large photographic sample and a small ground sample was conducted by the Northern Region of the USDA Forest Service using double-sampling with
regression (Wear et al. 1966, chapter 6, section 6.10.1) to estimate the number of trees killed and volume loss in 1970 and 1971 (Ciesla et al. 1971b).

The general area of infestation was established by aerial sketchmap surveys. This was followed by an aerial photographic stage consisting of 100 aerial photographic plots established in a more or less random pattern over the infested area (chapter 4, Figure 4.5). The aerial photographs were taken in August 1971 at a scale of 1:8,000 with CIR (Kodak 2443) film using a 9-inch aerial camera with a 6-inch lens. Stereoscopic pairs (60 percent overlap) were taken over each photographic plot. A 100 acre photographic plot, 20 by 50 chains, was established in the stereoscopic overlap portion of each photographic pair. These were examined in stereo, and two independent photointerpreters made counts of the number of discolored Douglas-fir crowns (faders) for each plot. For the ground survey stage, 26 of the aerial photographic plots were randomly selected and a variable plot cruise (BAF 20) with 40 subplots established at 5-chain intervals on cruise lines 5 chains apart was conducted in each of the 26 ground plots. All trees in the subplots were recorded by species and measured for DBH and height. Douglas-fir were classified as:

0. Green, uninfested.
1. Attacked in 1971: green foliage and beetle brood present in cambium.

The four variables to be estimated—1970 trees, 1970 volumes, 1971 trees and 1971 volumes—were the dependent variables (y) and the photographic count of dead trees was used as the dependent variable (x) in the regression analysis.

The survey provided the required information (Ciesla et al. 1971b). However, photointerpreters encountered difficulty in distinguishing Douglas-fir beetle mortality from other damage, including mortality of western white pine from white pine blister rust and mountain pine beetle, and grand fir killed by fir engraver on the CIR photographs. Subsequent inventories of the outbreak were conducted in 1972 and 1973 using color film, and the various damage types were easier to assign (McGregor et al. 1972, McGregor et al. 1974).

7.1.1.3. Mountain Pine Beetle. During the late 1970s, a survey system was designed by Forest Pest Management/Methods Application Group (FPM/MAG) to provide estimates of losses caused by the mountain pine beetle, in ponderosa and lodgepole pine forests throughout the West. The objective of this project was to provide annual data on a statewide basis for:

- Area infested,
- Number of trees killed,
- Volume affected.

A conceptual multistage survey design consisting of three stages (chapter 4, Figure 4.6) was developed and consisted of:

1. Aerial sketchmapping to define the general area of infestation and to stratify intensity classes within the area of infestation,
2. Aerial photographic samples within each of the strata established from aerial
sketchmapping, and

3. Ground data acquisition on a small sample of aerial photographic samples.

A level of one fading tree per 10 acres was defined as the lower threshold for defining areas as
"infested" from the aerial sketchmap surveys. Aerial photographic samples were established on a
systematic grid within the infested areas and strata established by aerial sketchmapping. A 9-inch
stereoscopic triplet was taken at each photographic point with color positive transparency film
(Kodak SO-397) at a scale of 1:6,000. A 90-acre photographic plot, divided into thirty-six 2.5-acre
cells was established over the principal point of the center photograph of each triplet in ponderosa
pine forests and a 40-acre photographic plot, divided into sixteen 2.5-acre cells was established in
the same manner in lodgepole pine forests. Counts of the current year’s faders were made for each
2.5-acre cell on the aerial photographs. For the ground survey, a sample of PSU photographic
plots was randomly selected. Within each PSU, two 2.5-acre SSU cells were selected using a probability
PPS selection procedure based on counts of fading trees. The analytical procedure for this survey
method is described in detail in chapter 6, section 6.10.2, of this manual and by White et al. (1983).

This survey design was tested in ponderosa pine forests in the Black Hills of western South Dakota
and northeastern Wyoming, and along the Front Range of Colorado (Hostetler and Young 1979a
and 1979b) and in lodgepole pine forests on the Gallatin and Beaverhead National Forests, Montana
(Bennett and Bousfield 1979).

A second approach to acquire these data involved the use of high-altitude panoramic CIR (Kodak
SO-131) aerial photographs taken from the NASA ER-2 reconnaissance aircraft equipped with an
Itek KA80A panoramic camera system. The ability of this aircraft/camera system to cover large
areas of land in a short time provided an opportunity to obtain 100 percent area photographic
coverage of known areas of mountain pine beetle infestation, and to use the photographs for both the
first-stage stratification and the second-stage photographic counts. The major concern with this
approach was whether or not reliable counts of fading trees could be made on the smaller scale
(nadir scale 1:30,000) panoramic photographs.

A pilot survey of panoramic aerial photography to estimate mountain pine beetle losses was
conducted over mountain pine beetle infested lodgepole pine forests on the Gallatin National Forest,
Montana, in 1977 (Klein 1982a, Klein et al. 1980). In this survey, a three-stage variable probability
design was used in which sample units were selected based on probability proportional to size. The
first stage involved complete and rapid classification of the frames covering the outbreak. The
second stage involved tree counts on 120- to 160-acre cells selected with PPS from the first stage.
The third or final stage included ground data taken on 20 10-acre cells selected by PPS from the
second stage. Survey results and costs compared favorably to an aerial sketchmap/9-inch aerial
photography/ground survey conducted over the same area (Bennett and Bousfield 1979; Table 7.1).

Table 7.1. Comparison of costs and estimates of number and volume of lodgepole pine killed by
mountain pine beetle from two separate surveys conducted on the Beaverhead and Gallatin

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Similar surveys were conducted over ponderosa pine forests along the Front Range of Colorado in 1979 and 1980 (Dillman et al. 1981, Dillman and White 1982a, Eav et al. 1984). In 1979, some 5.5 million acres of the Front Range, from Colorado Springs to the New Mexico border (Figure 7.1) were included in the survey, which was compared to results from a simultaneously conducted survey using 9-inch aerial photography over the entire 12 million acres of Front Range ponderosa pine forests (Hostetler et al. 1979b). The survey area was subdivided into 373 PSUs, each consisting of an even-numbered frame of panoramic photography covered by an equal area grid at ±35° of nadir. Each PSU was subdivided into 132 cells or SSUs, and each SSU was subdivided into 25 equal-area sub-cells or TSUs of approximately 4.5 acres. The first stage involved a quick count of the number of faders in a sample of PSUs in which the number of faders occurring within each of the 132 SSUs was recorded. One SSU per frame was selected according to PPS for the third-stage sample. This consisted of one TSU selected from each of the 80 SSUs based on PPS to the fader count. Each TSU was visited on the ground and the number and volume of infested trees were tallied (Dillman and White 1982a). During the following year, a survey with a slightly modified design was conducted over the entire Colorado Front Range (Dillman et al. 1981, Eav et al. 1984) (Figure 7.1 and 7.2). A detailed PI guide for identifying trees killed by mountain pine beetle, forest vegetation types along the Front Range, and potential sources of commission error was published (Dillman and White 1982b).

A survey of all major areas of mountain pine beetle outbreaks throughout the western United States was conducted in 1980 and 1981 using both aerial sketchmapping and either 9-inch aerial photography or panoramic aerial photography. This resulted in the data summarized in Table 7.2 (Hofaker and Loomis 1982, White et al. 1983).
Both survey designs met their stated objectives; however, they were considered to be too time-consuming and labor-intensive to be conducted on a regular basis.

In western Canada, a similar multistage approach to inventory of mountain pine beetle infestations was developed and tested in 1980 over a 14,750-hectare (approximately 36,550-acre) area in the Flathead River Valley of southeastern British Columbia (Harris et al. 1982). Lodgepole pines killed by mountain pine beetle were sketchmapped. The second stage consisted of twenty-six 1-hectare (approximately 2.5-acre) photographic plots selected from a systematic grid. These were photographed with color positive transparency film (Kodak MS Aerochrome 2248) using twin 70-mm cameras mounted on a boom attached to a Bell 206B Jet Ranger helicopter. At each plot, three stereoscopic pair frames were taken at an approximate photographic scale of 1:5,000. Actual photographic scale for each plot was determined using the ratio of the camera base, 6.1 meters (approximately 20 feet) between cameras, to the same distance measured on the photographs. Counts of red (fading) and gray lodgepole pines were made on the 1-hectare aerial photographic plots. This was followed by ground examination of a sub-sample of nine 0.25-hectare (0.6-acre) ground plots on which all lodgepole pines were classified as healthy, green-attacked, red or gray, and by diameter class.

<table>
<thead>
<tr>
<th>State</th>
<th>Land ownership class</th>
<th>Acres infested (thousands)</th>
<th>Trees killed (thousands)</th>
<th>Volume killed (MCF)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colorado</td>
<td>National Forest</td>
<td>61.7</td>
<td>38.4</td>
<td>574.8</td>
</tr>
<tr>
<td></td>
<td>Other Federal</td>
<td>0.5</td>
<td>0.4</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>State &amp; Private</td>
<td>19.7</td>
<td>15.6</td>
<td>232.4</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>81.9</td>
<td>54.4</td>
<td>814.6</td>
</tr>
<tr>
<td>Montana</td>
<td>National Forest</td>
<td>18.9</td>
<td>8.1</td>
<td>53.6</td>
</tr>
<tr>
<td></td>
<td>Other Federal</td>
<td>6.4</td>
<td>2.7</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>State &amp; Private</td>
<td>51.4</td>
<td>21.7</td>
<td>145.1</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>76.4</td>
<td>32.5 ±8.6%**</td>
<td>216.9±9.0%</td>
</tr>
<tr>
<td>Oregon</td>
<td>National Forest</td>
<td>43.1</td>
<td>50.7</td>
<td>707.9</td>
</tr>
<tr>
<td></td>
<td>Other Federal</td>
<td>0.7</td>
<td>0.8</td>
<td>11.1</td>
</tr>
<tr>
<td></td>
<td>State &amp; Private</td>
<td>23.8</td>
<td>27.6</td>
<td>387.1</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>67.6</td>
<td>79.1±16.6%</td>
<td>1,106.1±35.5%</td>
</tr>
<tr>
<td>South Dakota</td>
<td>National Forest</td>
<td>177.3</td>
<td>280.4</td>
<td>4,766.8</td>
</tr>
<tr>
<td></td>
<td>Other Federal</td>
<td>13.8</td>
<td>21.8</td>
<td>370.6</td>
</tr>
<tr>
<td></td>
<td>State &amp; Private</td>
<td>38.9</td>
<td>61.4</td>
<td>1,043.8</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>230.0</td>
<td>363.6</td>
<td>6,181.2</td>
</tr>
<tr>
<td>Utah</td>
<td>National Forest</td>
<td>7.8</td>
<td>164.1</td>
<td>5,133.3</td>
</tr>
<tr>
<td></td>
<td>Other Federal</td>
<td>0.1</td>
<td>1.8</td>
<td>54.6</td>
</tr>
<tr>
<td></td>
<td>State &amp; Private</td>
<td>0.4</td>
<td>8.7</td>
<td>273.0</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>8.3</td>
<td>174.6±4.0%</td>
<td>5,460.9 ±7.0%</td>
</tr>
<tr>
<td>Washington</td>
<td>National Forest</td>
<td>5.3</td>
<td>4.9</td>
<td>2,310.3</td>
</tr>
<tr>
<td></td>
<td>Other Federal</td>
<td>3.2</td>
<td>2.9</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>State &amp; Private</td>
<td>17.4</td>
<td>16.1</td>
<td>722.5</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>25.9</td>
<td>23.9±20.2%</td>
<td>417.4±46.7</td>
</tr>
<tr>
<td>Wyoming</td>
<td>National Forest</td>
<td>9.1</td>
<td>134.9</td>
<td>2,310.3</td>
</tr>
<tr>
<td>***</td>
<td>Other Federal</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>State &amp; Private</td>
<td>9.4</td>
<td>42.5</td>
<td>722.5</td>
</tr>
<tr>
<td></td>
<td>TOTAL</td>
<td>18.5</td>
<td>178.4</td>
<td>3,032.8</td>
</tr>
</tbody>
</table>

* Does not include National Parks, National Monuments, or other dedicated areas.
** Relative standard error. These estimates do not include infested trees removed as a result of suppression projects, salvage operations, or fuelwood gathering.
*** Estimates made from aerial sketchmap surveys.

This survey produced data equivalent to that produced in the U.S. using 9-inch or large format, panoramic aerial camera systems. Sampling error was 18.5 percent for tree counts and 38.9 percent
for volume estimates. Costs of the survey were $0.85/hectare ($0.34/acre) (Canadian) for the entire survey. Based on this survey, the participants recommended use of 1:6,000-scale, 70-mm aerial photography in combination with aerial sketchmapping, 4-hectare aerial photographic plots, and 0.25-hectare photo-ground sample subplots (Harris et al. 1982).

### 7.1.2. Forest Decline

#### 7.1.2.1. Beech Bark Disease–West Virginia

Beech bark disease (chapter 3, section 3.3.4) was discovered on the Monongahela National Forest, West Virginia, in 1981, some 300 air miles from the previous known range of this condition (Mielke et al. 1982). Subsequent aerial and ground surveys established that over 100,000 acres of northern hardwood forests on the Monongahela National Forest, a small portion of the George Washington National Forest, Virginia, and intermingled private lands were affected.

In 1983, a special survey was conducted by the Morgantown, West Virginia, Field Office of the Northeastern Area’s State and Private Forestry (S&PF) group in cooperation with FPM/MAG. The objective of this survey was to evaluate the suitability of 9-inch CIR aerial photography as part of a multistage sampling system to determine the area affected, assess the damage caused by the disease, and estimate potential resource impact.

Approximately 50,000 acres, consisting of five blocks ranging in size from 8 to 25 square miles, were included in the survey. These were photographed with CIR (Kodak 2443) film at 60 percent overlap and 20 percent sidelap. In addition, a test strip was flown over one block at a scale of 1:4,000 with both CIR and color positive transparency film (Kodak SO-397). The test strip served as a means of comparing damage signatures as they appeared on CIR film with what could be seen by the human eye.

The photographs were first used to stratify the area of aerially visible damage. This was followed by establishment of a 40 acre photographic plot on every fourth photograph falling within the area classified as having aerially visible damage. A total of 41 photographic plots were established in this manner. Each photographic plot was subdivided into sixteen 2.5-acre subplots, and counts were made of acutely chlorotic dying and dead trees with the aid of a dichotomous PI key developed to aid photographic interpreters (Figure 7.3). Ground plots were selected using the PPS method developed for inventory of tree mortality caused by mountain pine beetle (White et al 1983; chapter 6, section 6.10.2).

The survey established that tree mortality and decline due to beech bark disease was present over an area of 17,986 acres at the time of the survey. Some 11,922 trees, representing a net volume of 319,512 cubic feet (SE = 30.9 percent) were affected (Mielke et al. 1984).
1. Crown with little or no foliage, bare branches visible ........................................... go to 2.
1a. Crown with foliage ........................................................................................................... go to 3.

2. Branch pattern dendritic, color light gray (190 l.b. gray, 264 l. gray)..Dead hardwood
2a. Branches radiating from a central mainstem, color white or light gray (263 white, 264, l.gray, 190 l.b. gray)..............................Dead red spruce

3. Foliage color red, magenta, red brown or beige ........................................... go to 4.
3a. Foliage color pink, yellow or white ................................................................. go to 5.

4. Crown shape rounded, foliage color red, magenta or light reddish brown (living hardwood vegetation)........................................................................................................... go to 6.
4a. Crown shape spire-like, foliage color red brown (40 s.r.br. or 16 d. red) or light brown near sunspot (42 l.r. br)..............................Living red spruce

5. Foliage color yellow or olive green yellow ............................................................. go to 7.
5a. Foliage color white or pink ......................................................................................... go to 8.

6. Foliage color light reddish brown (42 l. gy.r.br. or 45 l. gy.r.br), foliage fine textured .................................................................Leaf mining of black locust by locust leaf miner
6a. Foliage color red or magenta (3 deep pink, 12 s. red, 28, d.p.pk or 251 d.p.pink).............................. Living hardwood

7. Crown shape rounded, foliage color yellow (82 v. yellow or 83 brill yellow).................................................................................................................................Dying hardwood
7a. Crown shape spire-like, color yellow or green yellow (109 l. gy. ol. or 112 l.ol.gray)..............................Living red spruce

8. Foliage color pink (41 pink or 5 m. pink).............................................................Slightly chlorotic hardwood
8a. Foliage color white or light pink (263 white or 9 pk. White).........................................................Acutely chlorotic hardwood

* Notations in parenthesis refer to designations on National Bureau of Standards ISCC-NBS color chips (Smith and Anson 1968). They are provided for a general description of foliage color. Actual foliage color may vary slightly.

Figure 7.3. Dichotomous key used to aid in classification of crown condition on CIR photographs in areas affected by beech bark disease, Monogahela National Forest, West Virginia (Mielke et al. 1984).

7.1.2.2. Decline And Mortality of Spruce-fir Forests–Eastern U.S. During the mid-1980s, there was considerable concern about the condition of high-elevation spruce-fir forests in the Appalachian and Adirondack Mountains. This concern followed several reports indicating substantial reductions in the basal area of some size classes of red spruce, and, to a lesser degree, balsam fir. Acid rain was suggested as one of the possible causes of this phenomenon (Johnson and Siccama 1983, Vogelmann...
1982). As a result of this concern, surveys of the condition of the high elevation spruce-fir forests were conducted in parts of New Hampshire, New York, and Vermont (Weiss et al. 1985a and 1985b), West Virginia (Mielke et al. 1986) and the Southern Appalachian Mountains (Dull et al. 1988). Since these inventories involved large, often remote areas, all included a remote-sensing component.

During the period July 1984 to January 1995, a multistage inventory to determine the extent of tree mortality in the spruce-fir forests of New Hampshire, New York, and Vermont was conducted by the Durham Field Office of the Northeastern Area, State and Private Forestry, USDA Forest Service, and respective state forestry agencies, with technical support from FPM/MAG. The survey design was modeled after the multistage survey for mountain pine beetle (section 7.1.1.3.) and consisted of a combination of two stages of aerial photointerpretation and one stage of ground surveys.

The area included in the inventory was subdivided into four survey regions as follows (Figure 7.4):

- New York - Tug Hill Plateau
- New York - Adirondack Mountains
- Vermont - Green Mountains and Central Plateau
- New Hampshire - White Mountains and Western Highlands

Sample blocks, consisting of a quarter of a USGS 1:24,000 map sheet, (8,000 acres) were randomly selected as aerial photographic sample blocks in each survey region (Figure 7.4.). These were photographed at a scale of 1:8,000, with 9-inch CIR film (Kodak type 2443). Four flight lines of about 14 photographs each were required to provide 60 percent overlap and 30 percent sidelap.

Photointerpretation consisted of stratification of the 8,000-acre blocks into vegetation types and tree mortality classes using PI guidelines specifically developed for this project (Ciesla 1984a).

Each of the photograph blocks was stratified into five vegetation types with a minimum 10-acre polygon size as follows:

- **Spruce-fir bog** – Low-lying bogs or swamps with more than 50 percent of the overstory in spruce and/or fir.
- **Spruce-fir slope** – Areas with more than 50 percent of the overstory composed of spruce and/or fir.
- **Mixed-wood** – Areas with 25-50 percent spruce or fir.
- **High elevation balsam fir** – A subclass of the spruce-fir slope where more than 90 percent of the stand was composed of balsam fir with small crowns and an average diameter of less than 5 inches DBH.
- **Other** – All other areas including lakes, fields, other forest cover, and alpine or tundra vegetation.
Each of the vegetation types with a spruce-fir component was then stratified into one of three spruce-fir mortality classes:

1. **Light** - Less than 10 percent standing dead spruce and fir.
2. **Moderate** - Between 10 and 30 percent standing dead spruce and fir.
3. **Heavy** - More than 30 percent of standing dead spruce and fir.

A second stage of PI involved making counts of dead and dying spruce and fir on 2.5-acre photographic plots within each of the vegetation type/mortality strata. This was followed by a ground survey of a small sample of the 2.5 acre cells on the photographic plots in which all standing dead spruce and fir (snags excluded) greater than 5.0 inches DBH were tallied.

This survey provided estimates of the area of spruce-fir type by vegetation/mortality strata within each of the survey units (Table 7.3), estimates of the number of dead trees within each of these strata (Table 7.4.), and data on levels of mortality by elevation zones, possible causal factors, and effects on regeneration (Weiss et al. 1985a and 1985b).
Table 7.3. Area of spruce-fir forest for the Vermont survey area by vegetation/tree mortality class as determined by interpretation of 1:8,000-scale CIR aerial photographs (Weiss et al. 1985).

<table>
<thead>
<tr>
<th>Mortality Class/Vegetation Type</th>
<th>Area (acres)</th>
<th>Standard Error of the Mean (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIGHT</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed-wood</td>
<td>99,000</td>
<td>24</td>
</tr>
<tr>
<td>Spruce-fir slope</td>
<td>103,000</td>
<td>34</td>
</tr>
<tr>
<td>Spruce-fir bog</td>
<td>9,200</td>
<td>76</td>
</tr>
<tr>
<td>TOTAL</td>
<td>211,200</td>
<td>32</td>
</tr>
<tr>
<td>MODERATE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed-wood</td>
<td>17,000</td>
<td>39</td>
</tr>
<tr>
<td>Spruce-fir slope</td>
<td>17,200</td>
<td>34</td>
</tr>
<tr>
<td>Spruce-fir bog</td>
<td>8,000</td>
<td>100</td>
</tr>
<tr>
<td>TOTAL</td>
<td>42,200</td>
<td>48</td>
</tr>
<tr>
<td>HEAVY</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mixed-wood</td>
<td>3,900</td>
<td>86</td>
</tr>
<tr>
<td>Spruce-fir slope</td>
<td>12,400</td>
<td>53</td>
</tr>
<tr>
<td>Spruce-fir bog</td>
<td>5,900</td>
<td>74</td>
</tr>
<tr>
<td>TOTAL</td>
<td>22,200</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 7.4. Number and gross volume of standing dead spruce and balsam fir (≥5.0 inches DBH) by cover type and mortality class, Vermont survey regions as derived from photographic plots and ground surveys, 1984 (Weiss et al. 1985).

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>Mortality Class</th>
<th>Number of Dead Trees</th>
<th>Volume of Dead Trees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed-wood</td>
<td>Light</td>
<td>1,000,000 (25)*</td>
<td>10,060,000 (25)</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>180,000 (39)</td>
<td>1,790,000 (39)</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>60,000 (86)</td>
<td>620,000 (86)</td>
</tr>
<tr>
<td></td>
<td>ALL CLASSES</td>
<td>1,240,000 (21)</td>
<td>12,470,000 (22)</td>
</tr>
<tr>
<td>Spruce-fir slope</td>
<td>Light</td>
<td>1,030,000 (34)</td>
<td>10,360,000 (34)</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>260,000 (35)</td>
<td>2,580,000 (35)</td>
</tr>
<tr>
<td></td>
<td>Heavy</td>
<td>210,000 (54)</td>
<td>2,050,000 (54)</td>
</tr>
<tr>
<td></td>
<td>ALL CLASSES</td>
<td>1,500,000 (25)</td>
<td>14,990,000 (26)</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td>2,740,000 (17)</td>
<td>27,460,000 (17)</td>
</tr>
</tbody>
</table>

*Percent standard error in parenthesis.

In 1985, an evaluation was made of the condition of high-elevation red spruce forests on the Monongahela National Forest and intermingled state and private lands in West Virginia by the Morgantown, West Virginia Field Office, Northeastern Area S&PF, USDA Forest Service with technical assistance provided by FPM/MAG. For this evaluation, high-altitude, panoramic CIR (Kodak SO-131) aerial photographs, taken from a NASA ER-2 aircraft, were acquired over the
entire area where native red spruce was known to occur. A key to identification of stands with a conifer component was developed based on preliminary PI and ground examinations (chapter 4, Figure 4.1). Stands with a red spruce component were ultimately stratified into polygons of three vegetation types and three mortality classes on the aerial photographs (Table 7.5).

Table 7.5. Vegetation types and mortality classes used in classification of forests with a spruce component, Monongahela National Forest and adjoining areas, West Virginia, 1985 (Mielke et al. 1986).

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>Mortality Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conifer with spruce component (C) (&gt; 50% conifer)</td>
<td>1 - &lt;10%</td>
</tr>
<tr>
<td></td>
<td>2 - 10-30%</td>
</tr>
<tr>
<td></td>
<td>3 - &gt;30%</td>
</tr>
<tr>
<td>Mixed-wood with spruce component (M) (≥25% but ≤50% conifer)</td>
<td>1 - &lt;10%</td>
</tr>
<tr>
<td></td>
<td>2 - 10-30%</td>
</tr>
<tr>
<td></td>
<td>3 - &gt;30%</td>
</tr>
<tr>
<td>Spruce plantation (P)</td>
<td>1 - &lt;10%</td>
</tr>
<tr>
<td></td>
<td>2 - 10-30%</td>
</tr>
<tr>
<td></td>
<td>3 - &gt;30%</td>
</tr>
</tbody>
</table>

Four flight lines, of about 60 miles each, were required to cover the target area. The photographs acquired for this mission had an exposure gradient across each of the photograph frames. A portion of each photograph east of nadir was slightly underexposed, the midsection was optimally exposed, and the region west of nadir was slightly overexposed. The exposure gradient caused a dramatic shift in the color of the coniferous vegetation, ranging from a dark to medium red-purple in the optimal and underexposed segments of each frame to a light purplish-blue in the underexposed regions. Spruce stands that appeared on the easternmost portion of one of the flight lines was so dark that tree mortality classes could not be stratified. Despite this problem, 71.2 percent of the vegetation types were classified correctly on the aerial photographs when compared with ground data taken from 66 polygons (Table 7.6).

Some 110,685 acres of forest land was classified as having a red spruce component with 1,603 acres as having mortality equal to or greater than 30 percent (Table 7.7). The survey estimated that declining and dead spruce trees represented 33 percent of the total red spruce volume in the area. A stem canker caused by the fungus *Valsa kunzei* was the most frequent biotic agent associated with the declining trees (Miekle et al. 1986).
Table 7.6. Error matrix of aerial photographic classification of coniferous vegetation types on high-altitude panoramic photographs versus ground classification, Monongahela National Forest, West Virginia, 1985 (Mielke et al. 1986).

<table>
<thead>
<tr>
<th>Vegetation Class on Aerial Photographs (polygons)</th>
<th>Class</th>
<th>Other</th>
<th>Mixed wood</th>
<th>Spruce</th>
<th>Plantation</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Mixed-wood</td>
<td>0</td>
<td>7</td>
<td>1</td>
<td>0</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Spruce</td>
<td>10</td>
<td>1</td>
<td>9</td>
<td>0</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Plantation</td>
<td>6</td>
<td>0</td>
<td>1</td>
<td>29</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Total Error (%)</td>
<td>18</td>
<td>8</td>
<td>11</td>
<td>29</td>
<td>47/66 = 71.2%</td>
<td></td>
</tr>
</tbody>
</table>

Table 7.7. Forest area with a red spruce component by vegetation type and mortality class as determined from interpretation of high-altitude panoramic CIR photographs, Monogahela National Forest and adjoining lands, West Virginia, 1985 (Mielke et al. 1986).

<table>
<thead>
<tr>
<th>Vegetation Type</th>
<th>Mortality Class (acres)</th>
<th>Light</th>
<th>Moderate</th>
<th>Heavy</th>
<th>Unclassified</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed-wood</td>
<td>61,944</td>
<td>2,576</td>
<td>1,041</td>
<td>2,052</td>
<td>67,613</td>
<td></td>
</tr>
<tr>
<td>Conifer</td>
<td>31,936</td>
<td>3,718</td>
<td>562</td>
<td>5,119</td>
<td>41,335</td>
<td></td>
</tr>
<tr>
<td>Plantation</td>
<td>1,698</td>
<td>39</td>
<td>0</td>
<td>0</td>
<td>1,737</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>95,578</td>
<td>6,333</td>
<td>1,603</td>
<td>7,171</td>
<td>110,685</td>
<td></td>
</tr>
</tbody>
</table>

A survey was done by the Southern Region of USDA Forest Service beginning in 1984 to assess the condition of the high elevation spruce-fir forests in the Southern Appalachian Mountains of western North Carolina, eastern Tennessee, and southwestern Virginia. This area was of special interest because the fir component of these stands is Fraser fir, a species endemic to the Southern Appalachians. Moreover, this species has suffered extensive mortality due to the accidental introduction of the balsam woolly adelgid.
Objectives of this project were to:

- Delineate the boundaries of the spruce-fir forest and map its range in the Southeast.
- Classify and map the amount of tree mortality occurring within the spruce-fir forest.
- Analyze the relationship of tree mortality to other geographic features.

Data were obtained from a combination of aerial photography and ground inventories. Initially CIR 9-inch aerial photographs were obtained of all known areas of spruce-fir type at a scale of 1:12,000 during the summer (leaf on) season of 1984. This was followed by acquisition of 1:12,000-scale color (Kodak film type 2448) 9-inch photographs during the winter of 1995 (leaf off) to modify previously identified boundaries and damage strata for more detailed evaluations. Additional photographs were taken at a scale of 1:4,000 of previously established research plots.

For this project, spruce-fir type was defined as are stands containing dominant spruce and fir visible on the aerial photographs. Within the spruce-fir type, three mortality classes were recognized:

1. **Light** – Greater than 30 percent of the standing dominant and co-dominant trees dead.
2. **Moderate/heavy** - 30-70 percent of the standing dominant and co-dominant trees dead.
3. **Severe** – Greater than 70 percent of the standing dominant and co-dominant trees dead.

These strata were mapped on the aerial photographs and entered into a GIS.

A second stage of sampling on the aerial photographs consisted of establishment of 232 - 0.2 acre (0.809 ha) sample plots on the aerial photographs to estimate the number of dead spruce and fir. A sub-sample of ground plots was selected according to three elevation strata:

- below 5,200 feet.
- from 5,200 to 6,000 feet
- above 6,000 feet.

Analysis of the resultant data established that 65,752 acres of spruce-fir forest exist in the Southern Appalachian Mountains. Within these areas, 24 percent of the total area was classified as having severe mortality, 6 percent as moderate/heavy mortality, and 70 percent of the area was classified as having light mortality (Dull et al. 1988).

### 7.1.3. Root Disease

Aerial photographs of various scales and film types have been used to detect trees affected by various root diseases. Trees killed by annosus root rot, caused by the fungus, *Heterobasidium annosum (Fomes annosus)* have been detected in pine plantations in the eastern U.S. and Canada on CIR photographs (Murtha and Kippen 1969, Hadfield 1970). A series of annual aerial-photographic ground surveys were conducted in thinned shortleaf pine (*Pinus echinata*) plantations using 9-inch CIR aerial photography at a scale of 1:4,000 on the Shawnee National Forest, Illinois, to estimate annual mortality rates during the period 1968-69 (Hanson and Lautz 1969, Hanson et al. 1970, Hanson and Lautz 1971).
Johnson and Wear (1975) reported that the accuracy of classification of root disease centers caused by the fungus *Phellinus (Poria) weirii* in the Pacific Northwest varied with the area studied and the film/scale combinations used. Work in northern Idaho established that openings or “holes” in the forest canopy with dead and dying trees, indicative of root disease centers caused by *Armillaria mellea* and *P. weirii*, could be reliably identified on 9-inch CIR aerial photographs taken at scales of 1:4,000 or larger (Williams 1973). This led to an inventory of root disease losses on the Coeur d’Alene National Forest in northern Idaho via 1:4,000-scale CIR (Kodak type 2443) 9-inch aerial photography over a series of sample subcompartments. Stand openings suspected of being caused by root disease were classified on the photographs and subsequently examined on the ground and the portion of the area of each subcompartment occupied by root-disease-related stand openings was determined. This survey established that 5.5 percent of the commercial forestland on the Forest was occupied by root disease centers (Williams and Leaphart 1978).

### 7.1.4. Dwarf Mistletoe

Aerial photographs have been used to map and assess damage caused by the eastern dwarf mistletoe on black spruce, in the Great Lakes region. Meyer and French (1966) used sequential aerial photographs taken over a test site in northern Minnesota in 1940, 1951, and 1962 to estimate area infested and loss due to tree mortality caused by this parasite. In 1940, total area of infestation was estimated to be 67.3 acres. The infested area had expanded to 126.4 acres in 1962. Estimated tree mortality averaged 26 cubic feet/acre/year over the 22-year period. In a later study, Meyer and French (1967) determined that detection of dwarf mistletoe infections was possible through use of CIR film. Not only were old infection centers visible, but young infection centers in which mortality had not yet occurred were detected. Douglas (1973) determined that stand openings created by dwarf mistletoe in black spruce stands in northern Minnesota as small as 1/10-acre in size could be detected on scales as small as 1:118,000, and openings of 1/4 acre and larger were visible at a scale of 1:462,000. He describes the pattern of stand openings created by dwarf mistletoe infestation as “moth eaten.” French et al. (1975) reported that 35-mm CIR photographs taken at a scale of 1:30,000 provided adequate detection of dwarf mistletoe infection centers in black spruce stands in Koochiching County, Minnesota, and was also inexpensive.

Walters and Munson (1981) demonstrated the use of an aerial photographic sampling system for measuring timber volume loss caused by eastern dwarf mistletoe in portions of northern Wisconsin. Forty-two stands were selected on two forests and photographed with 9-inch CIR film at a scale of 1:8,000. Potential dwarf mistletoe centers were outlined on the transparencies. An area/density rating was then calculated for each center using the following formula:
Remote Sensing in Forest Health Protection _______________ Aerial Photography–Applications

\[ R = A \times D \]

where:

- \( R \) = Area/density rating
- \( A \) = Area of infection center (acres)
- \( D \) = Density rating of infection center on a scale of 1-4

1. = less than 25 percent of area in live trees
2. = 25-50 percent of area in live trees
3. = 51-75 percent of area in live trees
4. = greater than 75 percent of area in live trees

All possible infection centers detected on the aerial photographs that were also accessible were ground checked to determine dwarf mistletoe presence. A variable radius (basal area factor (BAF) = 10) plot was established within each center and in an uninfested portion of the stand near the infection center. Data collected on each tree were: DBH, height, and tree condition class:

1 = Live black spruce, no dwarf mistletoe
2 = Live black spruce, infected
3 = Dead black spruce, no dwarf mistletoe
4 = Live, other tree species
5 = Dead, other tree species

Eighteen accessible stands with 39 mortality centers were ground-checked. Of these, 13 stands and 27 mortality centers (69 percent) were infected by \( A. \) pusillum. Major sources of commission error were windthrow and mortality caused by flooding. Average volume loss attributed to dwarf mistletoe infection in the 549 acres included in the survey was 0.5 cords/acre.

7.1.5. Spruce Budworm

During the early 1970s, the extent and severity of damage caused by spruce budworm, \textit{Choristoneura fumiferana}, in Fundy National Park, New Brunswick, Canada, was classified and mapped on 1:10,000-scale CIR aerial photographs. Five mortality classes and five defoliation classes were recognized. The average volume loss per acre was determined by an independent ground sample of random cluster plots. It was established that the outbreak caused widespread tree mortality on 7,700 acres within the Park, with most of the mortality concentrated within 5,900 acres of spruce-fir forest. Twelve percent (353 cubic feet) of the total coniferous volume/acre was dead. The PI indicated that high tree mortality was concentrated in pure balsam fir stands, with smaller pockets of damage scattered throughout the Park. Average volume loss throughout the Park was estimated to be 40 cubic feet/acre (Murtha 1973a).
7.2. DAMAGE MAPPING

Damage mapping is defined as the production of maps of forest damage from remote sensing. Applications ranging from large-area mapping of insect defoliation in broadleaf forests and mapping of mortality in spruce fir forests to mapping of disease centers in live oak forests are summarized in the following sections.

7.2.1. Insect Defoliation of Broadleaf Forests

One of the more successful examples of the use of the NASA ER-2 high-altitude camera system has been for mapping of defoliation caused by the gypsy moth over portions of the Middle Atlantic states. Interest in the use of this technology for defoliation mapping began when massive outbreaks, encompassing millions of acres of broadleaf forest, occurred over portions of Pennsylvania, New Jersey, southern New York, Delaware, Maryland, West Virginia, and northern Virginia during the early 1980s. These outbreaks were so widespread that aerial sketchmapping, the standard method of defoliation mapping, had become an overwhelming task.

In 1981, a demonstration of the ability of panoramic CIR (Kodak SO-131) aerial photographs to resolve defoliation of broadleaf hardwood forests was conducted over a test site in central Pennsylvania by FPM/MAG in cooperation with the Morgantown, West Virginia Field Office of the Northeastern Area, S&PF (Ciesla and Acciavatti 1982). Photography was acquired on June 18, 1981, and included two north-south flight lines spaced at approximately 22.5 miles. Each line was about 76 miles long. The camera system used was the Itek Iris II. Resultant photographs had a nadir scale of approximately 1:31,000.

Quality of the resultant photographs was excellent within ± 40° of nadir. Defoliated forests were easily seen (Figure 7.5), appearing as tones of gray in marked contrast to the brilliant magenta and red hues of the undamaged forests. Photointerpreters could easily classify defoliation into one of three damage classes defined by the Pennsylvania Bureau of Forestry (chapter 6, section 6.9).

The photographs showed a clear shift in color balance toward cyan and a corresponding loss of resolution toward the extremities of each photographic frame. This was somewhat visible at 40° of nadir and intensified toward 70°. This shift was attributed to a combination of atmospheric haze and camera scan angle with respect to the sun. Heavy defoliation, however, could be discerned even at 70°, despite the loss of resolution. An “office sketchmapping” PI technique involving examination of the individual photographic frames on a light table in monoscopic mode was used to classify defoliation and transfer the defoliation polygons to a 1:24,000-scale USGS map base (Figure 7.6).
In 1983, a multi-state demonstration of this methodology was conducted over all or portions of Delaware, Maryland, New Jersey, and Pennsylvania. Mission planning, photograph acquisition, film processing, duplication and annotation was a cooperative undertaking involving three Federal agencies: USDA Forest Service, National Aeronautics and Space Administration (NASA), and the Environmental Protection Agency (EPA). After they had received PI training by specialists from the USDA Forest Service, personnel from the respective state agencies responsible for gypsy moth management programs completed photointerpretation and data transfer to a map base. A PI guide
describing the method for mapping hardwood defoliation and potential sources of PI error was published (Ward et al. 1986). All aspects of this project were successfully completed. However, photographs were acquired too early in the year for the appearance of peak hardwood defoliation in the mountainous regions of the project areas; this pointed out the need for more careful determination of photograph acquisition biowindows. Costs of photograph acquisition, film processing, and duplication for the 70,405 mi² area was $1.58/ mi², or $0.0025/acre (Ciesla et al. 1984b). Between 1984 and 1989, five additional multi-state surveys for mapping defoliation by gypsy moth were conducted, and the area of coverage was expanded to portions of West Virginia and northern Virginia as the outbreak area spread southward. Total project area ranged from 27,000 to 92,000 mi² at an average cost of $2.30/mi² or $0.0036/acre. State and federal agencies involved in gypsy moth management used the photographs to map defoliation, evaluate effectiveness of aerial spray projects directed against gypsy moth (chapter 7, section 7.3.1.2), and define areas of tree mortality after the outbreak subsided (Acciavatti 1990). The project was discontinued following a general decline of gypsy moth populations in the mid-Atlantic states.

7.2.2. Spruce-fir Mortality–Northeastern U.S.

In 1985, as a follow-up to the inventory of spruce-fir decline in the northeastern U.S. (Weiss et al. 1985a), a project was initiated to map the extent and severity of standing dead red spruce and balsam fir in the Adirondack Region of New York, the Green Mountains of Vermont, the White Mountains of New Hampshire, and the mountains of western Maine. Nine-inch, CIR aerial photographs, at a scale of 1:24,000, were acquired over approximately 4.6 million acres during the summers of 1985 and 1986.

Spruce-fir forests were stratified into the same vegetation/mortality classes used during the inventory conducted in 1984 (Weiss et al., 1985a, chapter 7, section 7.1.2.2.) by a team of aerial photointerpreters using the same guidelines developed for the spruce-fir decline inventory (Ciesla 1984b). These data were transferred to USGS 1:24,000 topographic maps and orthophotographs using a stereoscopic zoom transfer scope, and entered in a GIS maintained by the state of Maine (Maine Geographic Information System - MeGIS). Elevation contours of 2,600, 3,600 and 4,600 feet were also entered into the GIS as a separate data theme. Using the GIS, maps and tabular data were produced for each region summarizing the location and extent of the spruce-fir vegetation types and mortality classes in relation to elevational zones (Figure 7.7).

Over 700,000 acres of spruce-fir type was mapped on the 4.6 million acres. Approximately ⅔ of this area was classified as spruce-fir slope. Half of the total spruce-fir type was classified as having low mortality (less than 10 percent) and the remainder of the type was more or less equally divided between the moderate and heavy mortality classes (Miller-Weeks and Smoronk 1993). This work provides excellent baseline information from which changes in the distribution and future condition of spruce-fir forests in the northeastern U.S. can be measured.
Figure 7.7. GIS output showing levels of spruce-fir mortality in the Adirondack Mountains, New York, produced from interpretation of 1:24,000-scale CIR aerial photographs (Miller-Weeks and Smoronk 1993).
7.2.3. Ice Storm Damage–Northeastern U.S.

During January 1998, a severe ice storm struck portions of the northeastern United States and adjoining parts of Canada. Regarded as the “ice storm of the century,” the storm damaged over 17.5 million forests in Maine, New Hampshire, New York, and Vermont. While most states used aerial sketchmapping to map the extent of the damage, the Maine Forest Service acquired 1:9,000-scale “leaf off” color positive transparencies of about 2.8 million acres of southern Maine for damage mapping (Figure 7.8). These photographs were interpreted and the data stored in a GIS for production of detailed map of forest damage (USDA Forest Service 1998b).

CIR “leaf-on” aerial photographs, taken at a scale of 1:8,000 over portions of New Hampshire, New York, and Vermont, were used as reference data against which to compare results of aerial sketchmapping of ice storm damage. These photographs clearly resolved the damaged areas and permitted mapping to three damage classes, as follows (Ciesla and Frament 1999; Figure 7.9):

- **Light-Moderate Damage** - Occurrence of a scattering of broken, bent, or leaning trees amid a largely healthy forest canopy and/or presence of small openings caused by pockets of damaged trees, interspersed with areas of little or no damage.

- **Heavy Damage** - Presence of extensive areas of openings in the forest canopy through which the forest floor can be seen as a distinct white color, accompanied by large numbers of leaning, broken, or bent trees. These areas tend to have a mottled appearance because there is a scattering of trees with little or no damage.

- **No Visible Damage** - All areas of forest not classified as light-moderate or heavy.

Several conditions appearing on the CIR photographs were identified as potential sources of photointerpretation (commission) error, especially for photointerpreters with limited experience in interpretation of CIR film. These included:

- **Chlorotic (Yellow) Trees** - Broadleaf trees with chlorotic or yellow foliage appeared as pink or white (acute chlorosis) on CIR film. Occasionally, groups of chlorotic trees were seen. These typically occurred on steep slopes with shallow, low-nutrient soils. This signature is also typical of beech bark disease (chapter 3, section 3.3.4), known to be widespread in portions of the ice storm affected area. Another possible cause for the white foliage signature was attributed to early fall coloring of broadleaf trees that typically have yellow autumn foliage.

- **Conifer Mortality** - Conifer mortality, consisting of small groups of dead and dying red spruce were occasionally seen on the CIR photographs. Crowns had either a pale yellow-green, gray, or blue-grey hue. In some cases, they occur in mixture with tree crowns of the normal red-brown hue of healthy conifers.
Figure 7.8. Portion of a 1:9,000-scale color aerial photograph taken over a forested area in southern Maine damaged by the ice storm of January 1998.

Figure 7.9. Portion of a 1:8,000-scale CIR aerial photograph taken over the Bartlett Experimental Forest, White Mountain National Forest, New Hampshire showing damage by the ice storm of January 1998.
Recent Timber Harvesting Operations - Openings in the forest caused by recent timber harvesting operations were distinguished from ice storm damage by the presence of skid trails. These create a dendritic pattern of openings within the harvest unit.

Early Fall Coloring - This appeared as groups of trees with either bright yellow or white foliage, which in nature have red or yellow foliage, respectively. Early fall coloring appeared most frequently in low-lying wet areas where the dominant broadleaf tree is red maple.

Early Leaf Fall - In some areas of northern New York, paper or white birches had already lost their foliage. These areas appeared as a gray hue, with bare crowns visible, and could easily be confused with ice damage. However, these areas did not contain evidence of broken or bent trees.

7.2.4. Oak Wilt–Central Texas
Panoramic CIR (Kodak SO-131) aerial photographs taken at a scale of approximately 1:32,500 with a NASA ER-2 reconnaissance aircraft were evaluated in 1983 to detect centers of decline and mortality of Texas live oak in central Texas (chapter 3, Figure 3.18). The aerial photographs were interpreted monoscopically and then compared to results of PI of 1:12,000-scale 9-inch CIR aerial photographs using a GIS. The area of agreement, defined as common area classified on both films, was low—less than 20 percent.

The low level of agreement in classification of oak wilt centers was believed to be the result of several factors. One was the time difference between the acquisition of the two sets of aerial photographs: May 1983 for the panoramic photographs and August 1982 for the 9-inch photographs. This may have been a reason why a number of small centers were detected on the panoramic photographs and not on the 9-inch photographs. Another reason is that subtle symptoms of crown thinning could not be seen on the small-scale panoramic photographs. The major source of disagreement was a classic commission error: photointerpreters working with the panoramic photographs classified brush piles as areas of oak decline and mortality. Area ranches convert low grade juniper (Juniperus ashei) and broadleaf trees into rangeland by cutting and piling the trees, but photointerpreters were unfamiliar with ground conditions in the area.

This work indicated that panoramic, high-altitude CIR aerial photographs are a promising tool for mapping oak decline and mortality in central Texas, provided that experienced photointerpreters, familiar with the conditions on the ground are used. However, these photographs were of too small a scale to resolve trees with early symptoms of decline (Ciesla et al. 1984a).
7.3. **ASSESSMENT OF TREATMENT EFFECTS**

Aerial photography has proven to be a valuable tool for assessing the effects of various pest management tactics, such as application of chemical or biological sprays and thinning.

7.3.1. **Foliage Protection**

The effectiveness of aerial photography for assessment of foliage protected through application of aerial sprays directed against forest defoliators and the quality of application has been demonstrated in a number of locations across the United States. Assessment of foliage protection involves comparison of the level of foliar injury in treated areas with untreated checks or surrounding untreated areas. In order for this approach to be effective, damage caused by the insect must be aerially visible and areas immediately surrounding the treated area must be of the same vegetation type and contain similar population levels of the target pest (Ciesla 1984c). The following sections describe examples of how this approach has been used.

7.3.1.1. **Forest Tent Caterpillar–Southern Alabama.** The forest tent caterpillar (*Malacosoma disstria*) is an indigenous defoliator of temperate broadleaf forests throughout the eastern United States and Canada. Among the areas where periodic outbreaks occur are the low-lying water tupelo (*Nyssa aquatica*) forests in river basins of southern Alabama and Louisiana (chapter 3, Figure 3.26) (Ciesla and Drake 1970).

In 1970, insecticide trials were conducted on small plots infested by forest tent caterpillar in the Mobile River Basin by scientists of the Southern Forest Experiment Station’s Hardwood Insect Research Project in Stoneville, Mississippi. The test area had six to ten feet of standing water at the time of the test and was accessible only by boat. Moreover, the infested trees were tall (100 to 150 feet tall), making traditional insect population counts before and after treatment virtually impossible. Therefore an assessment of foliage protected by the aerial sprays using color and CIR aerial photography was conducted.

Flights were made of the test site in May 1970, when defoliation was at its peak. Both color and CIR photographs at scales of 1:6,000 and 1:15,000 were taken over the site. Plots protected by the aerial sprays were readily discernable on both films, but the CIR film provided greater contrast between the water tupelo forest and other broadleaf forest types. Moreover, there was greater contrast between classes of defoliation on the CIR film. The 1:15,000-scale photographs were superior to the 1:6,000-scale photographs because they permitted interpretation of a larger land area with a minimal loss of detail. One of the factors that could be evaluated was the quality of the aerial application because air currents caused insecticide droplets to drift away from the spray blocks, deposited them in non-target areas, and were resolved as areas of partial protection (Ciesla et al. 1971a) (Figure 7.10).

7.3.1.2. **Gypsy Moth–Northeastern U.S.** Thirty-five millimeter oblique color and CIR positive transparencies have been used successfully to demonstrate foliage protection achieved by application of aerial sprays directed against the gypsy moth in small experimental blocks (White et al. 1978.)
Figure 7.10. CIR photograph of a bottomland hardwood forest in the Mobile River Basin, Alabama, showing blocks with protected foliage due to aerial application of insecticides and area of partial foliage protection due to spray drift (original photographic scale = 1:15,000; Ciesla et al. 1971a).

Figure 7.11. High-altitude panoramic CIR aerial photograph showing area treated for gypsy moth suppression in Mifflin County, Pennsylvania, surrounded by heavily defoliated forests.
High-altitude panoramic CIR (SO-131) aerial photographs taken by the NASA ER-2 reconnaissance aircraft (chapter 7, section 7.2.1.1) for large area mapping of gypsy moth defoliation were also evaluated for their ability to resolve differences in levels of defoliation between areas treated for gypsy moth suppression and surrounding untreated areas. Forty-five irregularly shaped blocks, ranging in size from 6 to 264 acres, treated for gypsy moth control in Mifflin County, Pennsylvania during 1981 were evaluated using visual PI techniques. Two-thirds of the blocks showed differences in defoliation levels when compared to surrounding areas (Figure 7.11, Ciesla 1983). Similar high-altitude CIR photographs taken over portions of the gypsy moth infested area of the eastern U.S. during subsequent years revealed spray blocks with alternating bands of defoliation and non-defoliated forest, indicative of a spray aircraft flying at too wide a swath interval (Figure 7.12).

![High-altitude panoramic CIR aerial photograph showing area treated for gypsy moth suppression (dark areas at center) in northern Maryland, with alternating bands of defoliation and protected areas indicative of too wide of a spray application swath interval.](image)

**Figure 7.12.** High-altitude panoramic CIR aerial photograph showing area treated for gypsy moth suppression (dark areas at center) in northern Maryland, with alternating bands of defoliation and protected areas indicative of too wide of a spray application swath interval.

**7.3.1.3. Pandora Moth–Arizona.** In 1979, the pandora moth (*Coloradia pandora*), a defoliator of pines in the western U.S., reached epidemic levels in ponderosa pine forests on the Kaibab National Forest in northern Arizona. This led to a pilot control project in 1981 designed to assess the efficacy of aerial applications of the insecticide acephate (Orthene) to protect key scenic, timber, and wildlife resources in a scenic corridor leading to the North Rim of the Grand Canyon (Bennett and Ragenovich 1982).

CIR aerial photographs were taken at scales of 1:6,000 and 1:15,000 during two time periods: May 6, 1981, immediately prior to treatment, and June 26, 1981, when larval feeding was completed and defoliation was at its peak. The May photographs provided baseline data against which subsequent changes in foliage condition could be compared. This was important because conifers normally retain their foliage for several years (chapter 3, section 3.3.3.1) after initial attack; therefore, any
accumulated damage from previous years larval feeding might still be visible and not distinguishable from the 1981 generation of pandora moths.

Defoliation was classified into three intensity classes (undamaged, partial damage and heavy) on the aerial photographs and a defoliation map (Figure 7.13) was made of the test area relative to spray block boundaries. Defoliation mapped from the aerial photographs was compared with ground estimates of defoliation on sample plots established in each of the treatment blocks and untreated checks. The results of this evaluation indicated that there was a 74 percent agreement between aerial and ground classifications of defoliation. In the block where the insect population was significantly reduced by the insecticide application, the aerial photographs showed a corresponding area of reduced feeding injury (Figure 7.14). Blocks 1 and 2 received heavy rain and snow 7½ and 24 hours after treatment. Only block three showed an area of protected foliage (Ciesla et al. 1984c).

Figure 7.13. Map of 1981 pandora moth defoliation relative to treated blocks near Jacob Lake, Kaibab National Forest, Arizona. Blocks 1, 2, 3, and 5 were treated with acephate, and block 8 was an untreated check (redrawn from Ciesla et al. 1984c).
Figure 7.14. CIR aerial photographs of spray block 3, of the 1981 northern Arizona pandora moth pilot control project. The upper photograph was taken May 6, 1981, prior to treatment and appearance of defoliation by the 1981 generation of pandora moth. The lower photograph was taken June 26, 1981 at peak defoliation. The community of Jacob Lake is at approximate photograph center. Magenta to red areas are undamaged and the gray areas received defoliation. Area of undamaged foliage on the June 26 photograph conforms roughly to spray block boundaries (original photographic scale = 1:15,000) (Ciesla et al. 1984c).
7.3.2. Silvicultural Treatments

Thinning of overstocked, second growth stands of ponderosa pine (age ± 60 years, basal area > 100 ft²/acre) is known to prevent or reduce hazard of mountain pine beetle attack. The beneficial effect of thinning can be clearly seen on large-scale color or CIR aerial photographs by the lack of trees fading from bark beetle attack. In 1972, an inventory of tree mortality caused by mountain pine beetle was conducted in ponderosa pine stands on the Lolo National Forest, west of Missoula, Montana (Bousfield et al., 1973). Color aerial photographs at a scale of 1:6,000 were used as an intermediate sampling stage. One stereoscopic pair of the photographs resolved a recently thinned ponderosa pine stand surrounded by unthinned stands of a similar age class (Figure 7.15). The lack of recent tree mortality in the thinned stand, when compared to the unthinned stands, demonstrated to local resource managers and silviculturists the value of basal area reduction to prevent bark beetle infestations.

Figure 7.15. Portion of a 1:6,000-scale color aerial photograph taken over the Lolo National Forest, Montana, showing thinned and unthinned ponderosa pine stands. Note the lack of mountain pine beetle-caused mortality in the thinned stand.
7.4. OTHER APPLICATIONS

7.4.1. Forest Health Assessment–Vermont

Decline of sugar maple (*Acer saccharum*) was a major forest health concern in portions of the northeastern U.S. and adjoining Canada during the mid-1980s. In 1984, approximately 30,000 acres of hardwood decline and mortality, principally sugar maple, was mapped in Vermont (Teillon et al. 1985). The occurrence of sugar maple decline, coupled with the importance of the maple syrup industry in Vermont, led to the design and conduct of an assessment of the health of the state’s broadleaf forests.

Preliminary work was done in 1984 to characterize the symptoms of decline of broadleaf trees in Vermont as they appeared on CIR aerial photographs. Three sites in central Vermont were photographed at three photographic scales: 1:4,000, 1:6,000 and 1:8,000, with 9-inch format CIR film. Damage types seen on the photographs were described, and independent counts of dead and declining trees were made on photographs taken at each of the three photographic scales. These indicated that counts made from 1:8,000 photographs were no different from the two larger photographic scales. Pictorial and dichotomous keys to aid photo interpreters in classifying trees with symptoms of dieback and decline were prepared to aid photo interpreters (Ciesla et al. 1985; chapter 6, Figures 6.14-6.15).

The first of a series of hardwood tree health surveys was conducted in 1985 and 1986 using a two-stage aerial photographic/ground-based survey. The aerial photographic stage consisted of 170 360-acre aerial photographic plots, established on flight lines spaced at 7.4-mile intervals, with photographic points at 7.4-mile intervals. A strip of five 9-inch, 1:8,000-scale, CIR aerial photographs was taken at each photographic point.

A photographic plot was centered over the principal point of the center photograph of each flight strip. The photographic plot consisted of 144 2.5-acre cells established with the aid of a transparent overlay. Each cell was classified into one of the following five vegetation classes:

1. **Hardwood**: all cells with 50 percent or more of the forest cover and 75 percent or more of the forest canopy is hardwoods.

2. **Other Forest**: forested cells where 50 percent or more of the cell did not meet the criteria for hardwood type. This included mixed-wood and/or conifer forests.

3. **Nonforest**: all cells where 50 percent or more of the cell was not forested. This class includes agricultural areas, lakes, ponds, urban areas, etc.

4. **Cloud Cover**: all cells where 50 percent or more of the cell is obscured by clouds.

5. **Inundated**: all cells that meet the above criteria, but the forested area is flooded by water.
During the 1985 survey, hardwood stands were classified on the aerial photographs as either poletimber or sawtimber. This was discontinued in later surveys.

Cells classified as “hardwoods” were classified into one of three mortality classes:

1. **Light**: less than 10 percent of the hardwood canopy trees are dead.

2. **Moderate**: 10 to 30 percent of the hardwood canopy trees are dead.

3. **Heavy**: greater than 30 percent of the hardwood canopy trees are dead.

All of the cells in the “heavy” class, 50 percent of the cells in the “moderate” class and 5 percent of the cells classified as “light” were examined on the ground. Five sample points were established with a BAF 10 prism, and tree and site data were collected.

This survey provided data on the condition of Vermont’s hardwood forests, including statewide statistics on area of hardwood forest by mortality class, proportion of trees in various crown condition classes, and a ranking of hardwood tree health by species (Kelley and Eav 1987). The survey was repeated in 1991 (Kelley et al. 1992) and 1996 (Kelley et al. 1997). These surveys indicated a gradual improvement in crown condition of hardwoods over time, suggesting that the decline that began in the early 1980s had run its course. Several years of below-average precipitation and defoliator outbreaks preceded the decline episode, and improvements in crown condition may be related to decreased insect activity and above-average precipitation (Kelley et al. 1997).

The multitemporal nature of this survey provided a unique challenge: that of re-photographing the exact same sample blocks three times over a period of 10 years. This proved difficult in 1990; however, in 1995, the availability of an airborne GPS and a video camera facilitated navigation, and there was a high rate of success in capturing photography of the same sample blocks.

**7.4.2. Stand Hazard Rating For Douglas-fir Tussock Moth–Oregon**

A study was conducted in the Blue Mountains of eastern Oregon following an outbreak of Douglas-fir tussock moth between 1972 and 1974 to identify site and stand attributes associated with defoliation. These were measured on 9-inch CIR aerial photographs taken over 712 plots. A model was developed for predicting the probability of defoliation for a given set of conditions. In general, probability of defoliation was found to be higher in stands that:

- Were lower in elevation,
- Occupied east-facing slopes,
- Occupied ridgetops,
- Had high tree density,
- Contained trees of large crown diameter, and
- Consisted primarily of true firs and Douglas-fir.
Moreover, the probability of defoliation in a particular stand increased when defoliation had occurred in the area during the previous year or when surrounding stands were rated as having a high probability of defoliation (Heller et al. 1977.)

### 7.4.3. Bark Beetle Salvage Sales–California

Between 1975 and 1976, a severe drought in California led to an outbreak of several species of bark beetles. This resulted in an estimated loss of 13.4 million trees and about 1.6 billion cubic feet of timber between mid-1975 and June 1979 on National Forest Lands in the northern part of the state. In order to support planning of timber salvage sales in areas affected by bark beetle damage, entomologists with the Pacific Southwest Region of the USDA Forest Service arranged for acquisition of high-altitude CIR panoramic aerial photographs, using the NASA ER-2 aircraft, over about 40 million acres of forest land in northern California. Three separate photography missions were flown: July 1978, September-October 1978, and September 1979 (Figure 7.16). The photographs were made available to Forest Service officers on Ranger Districts who were involved in the planning and execution of the salvage sales. The photographs were used to help plan 223 salvage sales and resulted in a harvest of 532.2 million board feet of bark beetle-killed timber between July 1978 and May 1979 (Caylor et al. 1982).

![Figure 7.16. Forest area in California covered by panoramic aerial photography between July 1978 and September 1979 (Redrawn from Caylor et al. 1982).](image-url)
7.4.4. Mapping Port-Orford Cedar–Northern California and Southern Oregon

Color (Kodak SO-397) and CIR (Kodak 2443) positive transparencies taken at scales of 1:4,000 and 1:8,000 were evaluated for their ability to resolve stands with a component of Port-Orford cedar on the Siskiyou National Forest in southwestern Oregon and the Six Rivers National Forest in northern California. The purpose of this evaluation was to develop a capacity to identify stands that were not, as yet, infected by the root disease Phytophthora lateralis so that mitigating measures could be taken to protect these stands during timber harvesting, road construction or other activities. Both film types and scales were effective for resolving Port-Orford cedar and associated species. Port Orford cedar has a smooth crown texture and a distinct yellow-green color. This allows it to be differentiated from Douglas-fir, western hemlock, and other components of the forests in this area (Figure 7.17). Color film was found to be superior to the CIR film because it was easier to detect subtle color differences between certain tree species (Ciesla 1990, Ciesla and Hoppus 1990).

As a result of this work, foresters on the Siskiyou National Forest arranged for production of 1:12,000-scale positive transparencies from resource photography taken with color negative film. The positive transparencies provided greater color and tonal contrast than the color prints and resolved stands with a Port-Orford cedar component.

![Color aerial photograph taken over the Siskiyou National Forest, OR showing Port-Orford cedar in a mixed forest of Douglas-fir, western hemlock and Port-Orford cedar (original scale 1:4,000).](image-url)
7.4.5. Mapping Chemical Injury–British Columbia, Canada

The aerial extent of forest damage caused by the burning of elemental sulfur due to a train wreck in the North Thompson River Valley of British Columbia, Canada, was classified into four intensity strata on 9-inch, 1:12,000-scale CIR aerial photographs. Varying degrees of damage were classified over 11,300 acres on several tree species (Figure 7.18). Damage also occurred to alfalfa, but was quickly masked by new growth and did not appear on the aerial photographs. The damage extended for approximately 18 miles downwind from the burning train wreck (Murtha 1971).

Figure 7.18. CIR oblique photograph of damage to forest and other vegetation in British Columbia following exposure to burning sulphur (photograph courtesy of Peter A. Murtha, University of British Columbia, Canada).

7.4.6. Mapping an Exotic Plant in the Florida Everglades

The distribution of *Melaleuca quinquenervia*, an exotic and aggressive woody plant targeted for eradication, was mapped in the eastern Everglades using 1:7,000-scale 9-inch CIR aerial photography. The photographs were used in conjunction with GIS and GPS to produce a digital database of native and exotic vegetation within a 1.5 by 11 km study area. Hard copy maps were produced at 1:5,000-scale depicting plant species distributions and information on *M. quinquenervia* height and density classes interpreted from the CIR photographs. An accuracy assessment conducted from a helicopter indicated an overall map accuracy of 94 percent (McCormick 1999).
8. AIRBORNE VIDEO AND DIGITAL CAMERA SYSTEMS

This chapter reviews the characteristics and uses of two relatively new remote sensing tools of considerable interest in forest health protection: airborne videography and digital camera systems. Emphasis is placed on two systems that have been developed by the USDA Forest Service for natural resource remote sensing applications, including forest health monitoring.

8.1. AIRBORNE VIDEOGRAPHY

During the mid-1980s, improvements in image quality, affordability and portability of videography equipment made this technology increasingly viable as a remote sensing tool and several studies involving airborne videography for agricultural applications were reported (Nixon et al. 1984, Gerbermann et al. 1990, Edwards and Schumacher 1990, Mausel et al. 1990). A detailed review of airborne videography systems, their characteristics, and applications in natural resource management is presented by Everitt and Escobar (1990).

8.1.1. Strengths and Weaknesses

Airborne videography has several advantages over aerial sketchmapping and aerial photography that make it a desirable remote sensing tool for forest health protection (Myhre et al. 1990, Frament 1998).

- Video cameras and videotapes are less expensive than conventional aerial mapping cameras and film.
- Video imagery is available immediately after acquisition. This feature makes it particularly useful in applications requiring a rapid turnaround time, such as surveys of natural disasters and pest and fire damage.
- Videotapes, like aerial film, provide a permanent record of conditions as they exist at the time of data acquisition, thus reducing subjectivity.
- The ability to view live imagery on a monitor during image acquisition enables the operator to improve the quality of the data by changing exposure settings and adjusting for the area of coverage.
- The video-camera operator can record real-time audio input (commentary) as the data are collected.
- Video cameras tend to have a higher light sensitivity than film cameras. This allows imagery to be collected under less than ideal weather conditions.
- Video-camera systems can be easily installed in most of the small survey aircraft now used for aerial sketchmapping.
- Analog video imagery is easily converted from videotape tape to a digital format for image processing and incorporation into a GIS. Newer video cameras acquire data in digital format.
One drawback of videography imaging is its relatively narrow field of view. This makes the resultant imagery roughly equivalent to small format photography in terms of area coverage. Moreover, currently available videography systems provide an image resolution that is still significantly lower than aerial photographs.

8.1.2. Early Evaluations for Forest Health Protection

In 1986, a test was conducted to evaluate the operational feasibility of a CIR video camera for mapping forest defoliation and tree mortality caused by insects. The camera used in this test was a CIR video camera developed by the University of Minnesota’s Remote Sensing Laboratory and marketed under the trade name “Biovision.” This camera system is a modification of a professional grade, single-lens, three-tube camera modified to simulate the response of CIR film (Meisner and Lindstrom 1985, Everitt and Escobar 1990). This test indicated that the degree of mapping detail and the positional accuracy of polygons mapped by the video camera was superior to aerial sketchmapping. The discouraging part of the test was the relatively poor image resolution of the CIR video camera (Munson et al. 1988).

In 1988, following the CIR videography test, FPM/MAG evaluated the status of commercially available videography technology that could be adapted for acquisition of data of interest in forest health protection. The objective was to deploy videography systems to multiple field locations across the U.S. This evaluation (Myhre and Silvey 1992) provided the following information:

- Solid-state video cameras using charge-coupled device (CCD) sensors were superior to tube-type cameras and less prone to damage from vibration. This made them more suitable to aircraft operations.
- Shuttered video-image cameras were available that produce higher quality imagery by reducing blur from image motion and vibration that are part of airborne operations.
- A recording system known as Super-Video Home System (S-VHS) was available. This system had several advantages over the conventional VHS, including increased resolution, improved color quality, and an improved signal-to-noise ratio through increased band width.

8.1.3. USDA Forest Service Super-VHS Camera System

As a result of the evaluation conducted by MAG in 1998, an airborne video-image acquisition system was assembled using existing components to the extent that they were available commercially. The system has the flexibility to accept new and improved components as they become available and presently consists of the following components (Myhre and Silvey 1992; Figure 8.1).
Figure 8.1. The USDA Forest Service airborne videography system. Upper left - Panasonic 300 CLE video camera. Lower left - Airborne videography system components. Right - System installed in a Cessna 206 aircraft (photographs by Richard J. Myhre, USDA Forest Service, FHTET).

**Video Camera.** The video camera presently in use is a Panasonic CLE 300 with an S-VHS format and three CCD sensors responsive to blue, green, and red light, resulting in a true-color image. This camera has an electronic shutter with selectable speeds of 1/250 to 1/1,000 second, auto white/black balance, and 700-line horizontal resolution. It is equipped with a Canon 15x zoom lens, with focal lengths ranging from 9.5- to 143-mm (Figure 8.1; Myhre et al. 1992). The lens has a remote control feature for zooming and exposure or illumination control, an electronic viewfinder, and a tripod-mount adapter to attach the camera to the camera mount.

**Camera Mount.** A camera mount was designed to hold the camera in a vertical position over the aerial camera opening in the survey aircraft and make corrections for tip, tilt, and drift.

**Video Recorder.** A portable S-VHS recorder is used for recording both the video imagery and audio notes during each data acquisition mission.

**Video Monitor.** A color video-monitor is used during the data acquisition missions to observe what is being recorded and to adjust the camera for image quality.

**Power Converter.** The airborne videography system requires 12 volts DC to operate. Most aircraft have 24-28 volt DC power and require the use of a 24 volt DC-to-12 volt DC power converter.
Caption Generator. The caption generator links the video camera, recorder and an aircraft navigation system (GPS). This allows the camera operator to overlay date, time, latitude, longitude, and altitude onto the video frames. This information helps image interpreters locate and annotate the imagery.

Electrical Junction Box. A junction box was designed to help connect all of the various cables of the system.

Cabling. The total system requires a number of cables and connectors to link the various components. Most are commercially available while others are designed especially for this system.

A detailed users manual was developed by FPM/MAG (Myhre et al. 1992) for the installation and use of this system.

8.1.4. Mission Planning

8.1.4.1. Swath Width. The primary flight parameter for strip sampling with video imagery is the swath width of the sample strip. Since the Panasonic CLE S-VHS video camera has a zoom lens that provides a range of focal lengths between 9.5 and 143-mm, a range of flying height and lens focal length combinations can be used to achieve a desired swath width. However, since longer lens focal lengths tend to accentuate aircraft vibration on the images, it is a good policy to use the shortest possible focal length.

The flying height above ground level (AGL) for a given swath width can be determined as follows (Myhre et al. 1992):

\[ h = \frac{(D \cdot f)}{I} \]

where:

- \( h \) = AGL flying height in feet
- \( D \) = Desired swath width in feet
- \( f \) = lens focal length setting in inches
- \( I \) = Image width of a single video frame (8.8-mm or 0.3465 in)

For example, if a half-mile (2,640-ft.) swath width is desired and video imagery is to be acquired with a lens focal length setting of 9.5-mm, then:

\[
\begin{align*}
9.5\text{-mm} & = 0.95 \text{ cm/2.54 cm/inch} \\
& = 0.3740 \text{ inches} \\
\h & = \frac{(D \cdot f)}{I} \\
& = \frac{(2,640 \cdot 0.3740)}{0.3465} \\
& = 2,849.5 \text{ or 2,850 feet AGL}
\end{align*}
\]

AGL flying heights for various swath width/focal length combinations are given in Table 8.1.
Table 8.1. AGL flying height for various swath widths and lens focal lengths for airborne video image acquisition (source: Myhre et al. 1992).

<table>
<thead>
<tr>
<th>Swath Width</th>
<th>Resolution (feet)*</th>
<th>Flying Height (feet AGL) by Lens Focal Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miles</td>
<td>Feet</td>
<td>9.5mm (0.374 in)</td>
</tr>
<tr>
<td>0.125</td>
<td>660</td>
<td>1.65</td>
</tr>
<tr>
<td>0.25</td>
<td>1,320</td>
<td>3.30</td>
</tr>
<tr>
<td>0.50</td>
<td>2,640</td>
<td>6.60</td>
</tr>
<tr>
<td>0.75</td>
<td>3,960</td>
<td>9.90</td>
</tr>
<tr>
<td>1.00</td>
<td>5,280</td>
<td>13.20</td>
</tr>
<tr>
<td>1.25</td>
<td>6,600</td>
<td>16.50</td>
</tr>
<tr>
<td>1.50</td>
<td>7,920</td>
<td>19.80</td>
</tr>
<tr>
<td>1.75</td>
<td>9,240</td>
<td>23.10</td>
</tr>
<tr>
<td>2.00</td>
<td>10,560</td>
<td>26.40</td>
</tr>
<tr>
<td>2.50</td>
<td>13,200</td>
<td>33.00</td>
</tr>
<tr>
<td>3.00</td>
<td>15,840</td>
<td>39.60</td>
</tr>
<tr>
<td>3.50</td>
<td>18,480</td>
<td>46.20</td>
</tr>
<tr>
<td>4.00</td>
<td>21,120</td>
<td>52.80</td>
</tr>
</tbody>
</table>

*Image resolution is determined by dividing swath width in feet by 400 (400 lines on a S-VHS monitor).

8.1.4.2. Land Area of a Single Video Image. The land area (in acres) covered by an individual frame of video imagery is determined as follows:

\[
A = \frac{(W) \cdot (0.75W)}{43,560}
\]

where:

- \(A\) = Land area in acres
- \(W\) = Swath width in feet
- 0.75 = Height/width ratio of a video image
- 43,650 = Number of square feet/acre

For example, the area of a video image taken at a quarter-mile (1,320-ft.) swath width is:

\[
A = \frac{(1,320) \cdot (0.75 \cdot 1,320)}{43,560} = \frac{1,320 \cdot 0.75 \cdot 1,320}{43,560} = 30 \text{ acres}
\]

The land area covered by a video image taken at a 0.50-mile (2,640 ft) swath width is 120 acres.
To make as much use of a video sample strip as possible, determine the area in acres of the entire sample strip and divide by the area of a single video frame. This gives the total number of single frames to be classified. Determine the total lapsed time of the flight line in seconds. Divide the time in seconds by the number of frames to be sampled to get the interval between frames.

8.1.5. Image Interpretation and Processing

Once the video imagery has been collected, several options are available for image interpretation and/or processing.

The simplest technique is office sketchmapping. This is basically the same process used for transfer of information from aerial photographs to a map base described in chapter 7, section 7.2.1 and involves data transfer from a video-monitor to a map base on a flight line-by-flight line basis. Another approach is computer-screen sketchmapping. Videotapes imagery is converted to digital format, and a True Vision Targa 16 board is used to capture and digitize individual video frames for each flight line. Individual video frames can then be merged into flight lines and geo-rectified using image processing software. Polygons of damage are then identified on the computer screen and digitized directly into a GIS using a mouse. Finally, digital video imagery lends itself to computer assisted image processing. Software known as the Map and Image Processing System (MIPS) has been used for analysis of video imagery for forest health protection applications. This software allows the image analyst to annotate polygons of forest damage using a cursor on the computer screen and transfer the data into a GIS (Myhre and Silvey 1992; Figure 8.2).

Figure 8.2. Workstation for image processing of airborne video data (photograph by Richard J. Myhre, USDA Forest Service, FHTET).
An airborne video toolkit (AVT), which supports auto-mosaicking of still-frame video imagery has been developed through a cooperative effort involving FHTET, RSAC, and Colorado State University (CSU) (Linden and Hoffer 1994, Linden 1998). The AVT functions by integrating video data with differential GPS and aircraft altitude information. These data are recorded digitally on the videotape using Society of Motion Picture and Television Engineers (SMPTE) time codes. The videotapes are then post-processed using AVT software in conjunction with a robotic tape deck and a video frame grabber (Figure 8.3). The auto-mosaic software provides the following functions:

- Imports differentially corrected GPS data.
- Integrates tip/roll data with GPS data.
- Import USGS DLG-format files as reference maps.
- Displays flight lines and reference maps.
- Controls videotape recorder.
- Controls the frame grabber.
- Integrates simultaneous map and videography display.
- Provides for automatic frame-grabbing.
- Produces geometrically corrected image mosaics.

Figure 8.3. Display of individual video frames assembled by the AVT software (photograph by Richard J. Myhre, USDA Forest Service, FHTET).
This system was field tested during 1996 and 1997, and the average geometric accuracy of the mosaics was found to be acceptable (Linden 1998). The aesthetic value of the images was compromised, however, because of misalignment of linear features along frame boundaries. As a result, a follow-up project was conducted to incorporate auto-correlation techniques to correct feature alignments. This work is currently in progress and should also allow the AVT to automatically mosaic images from still-frame cameras as well as video cameras.

8.1.6. Applications

To simplify the initial transfer and implementation of the airborne videography system, the USDA Forest Service arranged for a consolidated procurement to ensure that all system users have the correct components and that the system will function as designed. As of 1992, ten systems were purchased and distributed to various Forest Service units (Myhre and Silvey 1992).

Some forest health applications of the airborne videography system are described in the following sections.

8.1.6.1. Southern Pine Beetle. Airborne videography has been used for monitoring and detection of southern pine beetle by the Southern Region of the USDA Forest Service in Alabama, Arkansas, Louisiana, and Texas (Figure 8.4). Quality hardcopy video imagery has been produced using specialized software. Because of the favorable results obtained for southern pine beetle monitoring, use of airborne video has been expanded to storm damage assessment, monitoring of the quality of silvicultural operations in longleaf pine forests, aquatic weed encroachment, and monitoring of damage caused by other pests (Spriggs et al. 1995).

Figure 8.4. Southern pine beetle, Dendroctonus frontalis, spot as seen on Super-VHS airborne video - National Forests and Grasslands in Texas (photograph by Richard J. Myhre, USDA Forest Service, FHTET).
Airborne video has been used in place of aerial sketchmapping for detection of southern pine beetle infestations on the National Forests and Grasslands in Texas. Areas are flown with the video camera system, data are transferred from videotapes to a computer, the images are geo-referenced and area infested, and numbers of infested trees and geographic position in relation to private lands and/or endangered species populations are computed. A number of mathematical models exist to predict southern pine beetle population growth. Multitemporal video images have been used to display the growth dynamics of infestations and to provide information that will more accurately predict infestation dynamics (Myhre and Silvey 1992).

8.1.6.2. Gypsy Moth. Two techniques using color airborne videography acquired by the USDA Forest Service S-VHS videography system were compared to aerial sketchmapping for mapping defoliation caused by gypsy moth (Figure 8.5). A single 7.5-minute USGS quadrangle map (1:24,000-scale) in central Michigan was used as a test site. The two airborne videography techniques evaluated were:

- Office sketchmapping
- Computer-screen sketchmapping - A True Vision Targa 16 board was used to capture and digitize individual video frames for each flight line. Individual video frames were merged into flight lines and geo-rectified using the MIPS image processing software. Flight lines were converted to ERDAS format, and defoliation was identified on the computer screen and digitized directly into a GIS using a mouse.

Figure 8.5. Defoliation of broadleaf forests by gypsy moth in central Michigan, as seen on Super-VHS video imagery (photograph by Richard J. Myhre, USDA Forest Service, FHTET).
Data obtained from aerial sketchmapping and the two airborne video techniques were compared to a reference data set. This consisted of a defoliation map made from PI of 1:11,000-scale CIR 9-inch aerial photographs. Results of this evaluation indicate that color aerial videography improved overall accuracy for mapping gypsy moth defoliation beyond that of aerial sketchmapping. Video office sketchmapping was the preferred method with the technology available at the time of the evaluation. However, with improvements in data collection and analysis capabilities, computer screen sketchmapping could become a more efficient and effective technique for mapping activities, and provide an effective blend of remote sensing, GPS, and GIS capabilities. Costs associated with aerial sketchmapping and video office sketchmapping for the survey were comparable: $229.36 for aerial sketchmapping versus $209.44 for video office sketchmapping. Computer screen sketchmapping costs for a single quadrangle were $3,282.84, and aerial photo interpretation costs were $1,716.56 (Buffington et al. 1992).

8.1.6.3. Forest Health Monitoring. A pilot project was conducted in Vermont in 1991 to determine the ability of airborne videography to support forest health monitoring. Objectives were to evaluate its capacity to enhance and supplement forest health monitoring ground activities and to determine the utility of the imagery for assessing the condition of individual trees and detecting changes in tree condition over time.

Video imagery was taken at swath widths of 1/8-, 1/4-, and 1/2-mile over a forested test site that was also photographed with 9-inch CIR aerial photographs at a scale of 1:4,000. Image interpreters then made counts of trees of various damage types on both the CIR aerial photographs and the three sets of video imagery (Table 8.2). Results showed that the 1/8-mile swath width had sufficient resolution to effectively detect trees of all damage types except snags. The 1/4-mile coverage was adequate for detecting trees with chlorotic (yellow) foliage and for the more obvious occurrences of crown dieback and tree mortality. The 1/2-mile strip coverage was only adequate for detecting chlorotic trees and, to some extent, dead trees with large crowns (Figure 8.6).

Table 8.2. Average counts of trees by damage type for all image interpreters on video imagery of three swath widths compared to 1:4,000-scale CIR aerial photographs, Vermont, 1991 (Frament et al. 1992).
This test demonstrated that airborne video is a useful supplement to traditional ground-based forest health monitoring methods, but had the disadvantage of low resolution when compared to aerial photographs and the scenes could not be viewed in stereo (Frament et al. 1992).

8.1.6.5. Assessment of Storm Damage. Strip sampling with the S-VHS airborne videography system and its GPS interface was used to assess forest damage caused by a severe storm on the Superior National Forest and adjoining state and private lands in northern Minnesota. A target site of 559,442 acres, the central portion of an area damaged by a storm that occurred on July 4, 1999, was selected for the evaluation. Thirty north-south flight lines were randomly established over the target site and flown with an altitude-lens focal length combination designed to produce a 0.25-mile-wide strip of video imagery.

Damage caused by the storm was clearly resolved on the video imagery (Figure 8.7), which was analyzed using visual interpretation. Damage was classified into three classes: light (10 to 33 percent), moderate (34 to 67 percent) and heavy (greater than 68 percent). Two methods of data capture were used and compared with an aerial sketchmap survey conducted immediately after the storm occurred. The first method involved classification of individual frames of video imagery along each flight line. The number of scenes in each class was multiplied by the area covered per image to compute the area of each damage class per flight line. The second data capture method involved analysis of the entire strip and recording times over each damage class. Times were converted to area using a simple ratio conversion. In addition, a map was produced from the imagery by plotting locations of classified damage onto the flight lines and interpolating between
flight lines. Both methods produced area estimates for each damage class with 95 percent confidence limits.

Figure 8.7. Super VHS airborne video image of storm damage to forests, Superior National Forest, Minnesota.

The statistical data (Figure 8.8) and the damage map (Figure 8.9) produced by the video imagery compared favorably with the results of the aerial sketchmap survey, leading to the conclusion that strip sampling with airborne video imagery is a viable alternative to aerial sketchmapping for rapid acquisition of data on the location and severity of forest damage caused by catastrophic climatic events and, possibly, insect-caused forest defoliation (Ciesla et al. 2000).
Figure 8.8. Comparison of estimates of forest damage caused by the July 4, 1999, storm derived from aerial sketchmapping and two methods of data capture from airborne video imagery, Superior National Forest, Minnesota (Ciesla et al. 2000).
Figure 8.9. Comparison of forest damage maps of the July 4, 1999, storm on the Superior National Forest, Minnesota, derived from analysis of airborne video imagery (above) and an aerial sketchmap survey on which square mile sections were classified (below) (Ciesla et al. 2000).
8.2. **DIGITAL CAMERAS**

Digital camera systems have recently become available and are now a popular consumer item. Prices are competitive with conventional film cameras and these systems could eventually replace film cameras for many photographic applications in the future.

Instead of recording images on photographic film, digital cameras focus light on a solid-state silicon-based charge-coupled device (CCD). The CCD consists of an array of separate photograph sites or pixels that convert light photons into electrons. The electrons produce a signal whose magnitude can be digitized, processed, and stored electronically (Bobbe et al. 1994). The resulting electronic image recorded by the CCD is stored in digital format on a hard drive such as a PCMCIA card. The card can be removed from the camera and inserted into the PCMCIA port of a PC. The digital images are subsequently exported into image processing or GIS software for viewing, enhancement, analysis, and printing.

Digital cameras can be used to complement other remote sensing data systems, such as aerial photographs or satellite imagery, to help create and update GIS databases. They can also provide high-quality images that can be geo-referenced using control points from 1:24,000-scale USGS maps or orthophotographs. The images can then be mosaicked into an orthophoto or other rectified image and exported into a GIS to use as a backdrop for updating or creating thematic layers (Bobbe et al. 1993).

Some other features of digital camera systems include (Bobbe et al. 1994):

- Little color bias and consistent recording of the same values when encountering the same color and brightness.
- A linear color response that prevents color shift through a range of brightness levels.
- A dynamic range over 10 to 11 f-stops, as compared to film, which typically has a dynamic range of 4 to 5 f-stops. CCDs are superior for imaging high-contrast scenes.
- Resultant images can be spectrally and spatially enhanced to improve image quality.
- Time and expense of film processing is eliminated.
- Digital images can be sent electronically to remote sites.
- Digital images can be combined with other digital vector and raster data.
- Digital images can be printed, copied, and inserted into documents such as technical manuals, work plans, and articles.

One of the first digital camera systems to be evaluated by the USDA Forest Service for remote sensing applications was the Kodak DCS 200 digital camera. This camera uses a one-CCD/one-shot design, and the CCD has 1.54 megapixels (1524-by-1012). Image capture is one color image every three seconds, and 50 images can be stored on the camera’s internal hard drive. The evaluation indicated that this camera was capable of producing a digital image with two to three times better
spatial resolution that the S-VHS airborne videography system. The primary limitation of the DCS 200 is its limited image storage capability (Bobbe et al. 1994).

### 8.2.1. Kodak Professional DCS 420 CIR Digital Camera

**8.2.1.1. System Configuration.** The Kodak Professional DCS 420 camera is an improved digital camera system consisting of a Nikon N90 camera body modified for digital image capture. The system will accept most Nikon lenses, but a 28-mm lens is most frequently used. The CCD chip is 13.7-mm wide and 9.1-mm high, and contains a 1524 x 1012 pixel array. Image storage is on a removable type III PCMCIA-ATA storage card, and is capable of storing 206 images on 340 MB of useable disk space. Disk space required for a single DCS 420 image is 4.5 MB plus about 0.1 MB for descriptive data including date, time, camera settings, and location (GPS position). This camera is capable of taking five images in just over two seconds, and can record approximately 1,000 images per battery charge. An AC battery charger/adapter provides unlimited power. The Kodak DCS 420 GPS camera contains a GPS interface (Eastman Kodak 1995, Knapp and Hoppus, 1996).

The Kodak Professional DCS 420 CIR camera (Figure 8.10) was developed by Eastman Kodak at the request of and with the cooperation of RSAC. This system has a spectral sensitivity ranging from 0.40 micrometers to 1.0 micrometers (visible light plus near-IR) and is capable of recording both color and CIR images simply by changing the lens filter (Eastman Kodak 1996). CIR images produced by this camera resemble CIR photographs taken with Aerochrome Infrared (type 2443) film. Of the digital camera systems currently available, the CIR digital camera has been of greatest interest in forest health protection because of its ability to simulate CIR aerial film.

![Kodak DCS 420 CIR digital camera system](image)

*Figure 8.10. Kodak DCS 420 CIR digital camera system (photograph by K. Andrew Knapp, USDA Forest Service, Boise, Idaho).*
8.2.1.2. **Spatial Resolution.** Resolution of the digital images is nearly equivalent to 35-mm color transparency film (approximately 55.5 lines/inch). However, because of the small size of the CCD chip in relation to 35-mm film, the system cannot produce high resolution images over comparable areas. A DCS 420 digital image with the same resolution as a 35-mm photograph will cover approximately seven times less land area (Table 8.3). When compared to the S-VHS airborne videography system, the DCS 420 has approximately six times the pixel resolution (Knapp and Hoppus 1996).

<table>
<thead>
<tr>
<th>Focal Length (mm)</th>
<th>Flying Height (ft AGL)</th>
<th>Image Scale (1:xxxx)</th>
<th>Land Area Covered (acres)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>35-mm</td>
</tr>
<tr>
<td>20</td>
<td>10000</td>
<td>15244</td>
<td>46.69</td>
</tr>
<tr>
<td>20</td>
<td>5000</td>
<td>76220</td>
<td>1167.28</td>
</tr>
<tr>
<td>20</td>
<td>10000</td>
<td>152439</td>
<td>4669.14</td>
</tr>
<tr>
<td>20</td>
<td>15000</td>
<td>228659</td>
<td>10505.56</td>
</tr>
<tr>
<td>28</td>
<td>10000</td>
<td>10889</td>
<td>23.82</td>
</tr>
<tr>
<td>28</td>
<td>5000</td>
<td>54443</td>
<td>595.55</td>
</tr>
<tr>
<td>28</td>
<td>10000</td>
<td>108885</td>
<td>2382.98</td>
</tr>
<tr>
<td>28</td>
<td>15000</td>
<td>163328</td>
<td>5359.98</td>
</tr>
<tr>
<td>35</td>
<td>10000</td>
<td>8711</td>
<td>15.25</td>
</tr>
<tr>
<td>35</td>
<td>5000</td>
<td>43554</td>
<td>381.15</td>
</tr>
<tr>
<td>35</td>
<td>10000</td>
<td>87108</td>
<td>1524.62</td>
</tr>
<tr>
<td>35</td>
<td>15000</td>
<td>130662</td>
<td>3430.39</td>
</tr>
</tbody>
</table>

Pixel resolution is expressed in feet and is a function of lens focal length, flying height, and the number of pixel elements on the CCD chip. Image pixel resolution, in feet, is computed for the DCS 420 and DCS 460 cameras (section 8.2.2.) as follows (Table 8.4):
Table 8.4. Image pixel resolution for the Kodak DCS 420 digital camera system at various lens focal length/flying height combinations.

<table>
<thead>
<tr>
<th>Focal Length (mm)</th>
<th>Flying Height (Ft AGL)</th>
<th>Pixel Resolution (Ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1000</td>
<td>0.45</td>
</tr>
<tr>
<td>20</td>
<td>5000</td>
<td>2.24</td>
</tr>
<tr>
<td>20</td>
<td>10000</td>
<td>4.48</td>
</tr>
<tr>
<td>20</td>
<td>15000</td>
<td>6.72</td>
</tr>
<tr>
<td>28</td>
<td>1000</td>
<td>0.32</td>
</tr>
<tr>
<td>28</td>
<td>5000</td>
<td>1.61</td>
</tr>
<tr>
<td>28</td>
<td>10000</td>
<td>3.22</td>
</tr>
<tr>
<td>28</td>
<td>15000</td>
<td>4.82</td>
</tr>
</tbody>
</table>

Example Exercise: Determine the resolution of a DCS 420 image taken with a 28-mm lens from a flying height of 10,000 feet AGL,

where:

\[ S = \text{photographic scale} \]
\[ H = \text{height AGL} \]
\[ f = \text{focal length} \]
\[ PR = \text{pixel resolution} \]

**Step 1.** Determine the total number of pixel elements on a CCD chip.

The pixel elements on a DCS 420 CCD chip are \( 1,524 \times 1,012 \) pixels = 1,542,288 pixels

**Step 2.** Determine photographic scale (S) of an image acquired at 10,000 feet AGL with a 28-mm focal length lens.

Convert all units of measure to a common scale (feet).

\[ 28 \text{ mm/}(10 \text{ mm/cm}) = 2.8 \text{ cm/2.54 cm/inch} \]
\[ = 1.10 \text{ inches/12} \]
\[ = 0.092 \text{ feet} \]
\[ S = \frac{H}{f} = \frac{10,000}{0.092} = 108,695.65 \text{ or } 1:108,695 \]

**Step 3.** Determine ground width of image at specified photographic scale.

Convert CCD chip width dimension from millimeters to feet.

- **Chip width**
  
  \[ = \frac{13.7 \text{ mm}}{10} = \frac{1.37 \text{ cm}}{2.54 \text{ cm/inch}} = \frac{0.54 \text{ inches}}{12} = 0.04494 \text{ feet} \]

- **Chip height**
  
  \[ = \frac{9.1 \text{ mm}}{10} = \frac{0.91 \text{ cm}}{2.54 \text{ cm/inch}} = \frac{0.36 \text{ inches}}{12} = 0.02985 \text{ feet} \]

- **Ground width**
  
  \[ = 0.04494 \times 108,695 = 4,884.75 \text{ feet} \]

**Step 4.** Determine ground length of image at computed photographic scale.

Convert CCD chip height dimension from millimeter to feet.

- **Chip height**
  
  \[ = \frac{9.1 \text{ mm}}{10} = \frac{0.91 \text{ cm}}{2.54 \text{ cm/inch}} = \frac{0.36 \text{ inches}}{12} = 0.02985 \text{ feet} \]

- **Ground length**
  
  \[ = 0.02985 \times 108,695 = 3,244.56 \text{ feet} \]

**Step 5.** Compute the land area of the area covered on the ground by the image:

\[ 4,884.75 \text{ ft} \times 3,244.56 \text{ ft} = 15,848,864 \text{ ft}^2 \]

**Step 6.** Compute the pixel resolution of the image:

\[ \text{PR} = \frac{\text{ground area}}{\text{pixel number}} = \frac{15,848,848}{1,542,288} = 10.28 = 3.20 \text{ feet} \]
8.2.1.3. Ability to Resolve Forest Damage. An initial evaluation of the ability of the Kodak DCS 420 CIR Digital Camera was conducted in the USDA Forest Service Intermountain Region during August and September 1995 using a small aircraft typically used in aerial sketchmap surveys. Flight altitudes ranged from 1,000 to 2,000 feet AGL, and a series of oblique images were acquired. The digital camera was hand-held and operated in a shutter-priority auto-mode, with a 1/500-second shutter speed and an ISO/ASA rating of 100. A 28-mm lens was used for all image acquisition. Whenever possible, corresponding color photography was collected concurrently with 35-mm cameras and Kodachrome 200 or Ektachrome 200 film. Forest damage included in this evaluation was typical of that encountered in the Intermountain Region and other parts of the western U.S. (Table 8.5).

Table 8.5. Damaging agents included in the initial evaluation of the Kodak DCS 420 digital CIR camera (Knapp and Hoppus 1996).

<table>
<thead>
<tr>
<th>Damaging Agent</th>
<th>Host</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Western pine beetle</td>
<td>Ponderosa pine</td>
<td>Boise National Forest, Idaho</td>
</tr>
<tr>
<td><em>Dendroctonus brevicomis</em></td>
<td><em>Pinus ponderosa</em></td>
<td></td>
</tr>
<tr>
<td>Douglas-fir beetle</td>
<td>Douglas-fir</td>
<td>Boise National Forest, Idaho</td>
</tr>
<tr>
<td><em>Dendroctonus pseudotsugae</em></td>
<td><em>Pseudotsuga menziesii</em></td>
<td>Dixie National Forest, Utah</td>
</tr>
<tr>
<td>Fir engraver</td>
<td>White fir</td>
<td>Uinta National Forest, Utah</td>
</tr>
<tr>
<td><em>Scolytus ventralis</em></td>
<td><em>Abies concolor</em></td>
<td></td>
</tr>
<tr>
<td>Spruce beetle</td>
<td>Engelmann spruce</td>
<td>Dixie National Forest, Utah</td>
</tr>
<tr>
<td><em>Dendroctonus rufipennis</em></td>
<td><em>Picea engelmannii</em></td>
<td></td>
</tr>
<tr>
<td>Douglas-fir tussock moth</td>
<td>Douglas-fir</td>
<td>Boise National Forest, Idaho</td>
</tr>
<tr>
<td><em>Orgyia pseudotsugata</em></td>
<td><em>Pseudotsuga menziesii</em></td>
<td>Subalpine fir</td>
</tr>
<tr>
<td></td>
<td><em>Abies lasiocarpa</em></td>
<td></td>
</tr>
<tr>
<td>Dwarf mistletoe</td>
<td>Ponderosa pine</td>
<td>Boise National Forest, Idaho</td>
</tr>
<tr>
<td><em>Arceuthobium spp.</em></td>
<td><em>Pinus ponderosa</em></td>
<td></td>
</tr>
<tr>
<td>Fire activity</td>
<td>Ponderosa pine</td>
<td>Boise National Forest, Idaho</td>
</tr>
<tr>
<td></td>
<td><em>Pinus ponderosa</em></td>
<td></td>
</tr>
</tbody>
</table>

Adobe Photoshop software was used to provide an optimum signature to background contrast for the image interpretation. The images were then examined by forest health specialists knowledgeable in forest damage signatures. Hardcopy of the images was produced using a Tektronix dye sublimation printer.

This evaluation indicated that the resulting images simulated color IR photographs and in virtually all cases, contrast between damaged and/or dying trees was enhanced compared to color photographs (Figure 8.8). This was especially true of scattered tree mortality such as that resulting from successive defoliations by Douglas-fir tussock moth or infestations of the fir engraver. This work concluded that the CIR digital camera can serve as a supplement to aerial sketchmapping, and
would increase accuracy of identification of the causal agent and quantification of number of trees affected (Knapp and Hoppus 1996).

Figure 8.8. Paired 35-mm color and CIR digital images of forest damage in the western U.S. The upper pair shows tree mortality caused by several successive years of feeding by Douglas-fir tussock moth, Orgyia pseudotsugata and the lower pair shows a group of ponderosa pines killed by the mountain pine beetle, Dendroctonus ponderosae (photographs by K. Andrew Knapp, USDA Forest Service, Boise, Idaho).

8.2.1.4. Flight Planning with the DCS 420 Digital Camera. In another evaluation of the CIR digital camera system, Lachowski et al. (1997) demonstrated its utility for mapping burn intensity in watersheds requiring emergency rehabilitation following wildfire. For this application, stereo coverage (60 percent overlap and 30 percent sidelap) was acquired with this camera system over a 30,000-acre watershed on the Mendocino National Forest, California. The flight pattern consisting of five flight lines at a flying height of 12,000 feet above MTE was flown with the aid of GPS navigation software. Some 150 individual images were acquired over the target area and mosaicked. The process of photography mission planning using the DCS 420 digital camera is similar to that used for conventional aerial camera systems. Instead of using the film dimensions to determine flight line interval and photographic point intervals; however, the dimensions of the CCD chip are used. The following problem illustrates this process.
Example Exercise: A Kodak DCS 420 digital camera equipped with 28-mm focal-length lens is to be used from a flying height of 10,000 feet AGL to acquire continuous imagery, with 60 percent overlap and 30 percent sidelap, over a block of land 3.25 miles wide and 4.2 miles long. Dimensions of the CCD chip on which the image is to be recorded are 13.7-mm wide and 9.1-mm high. Determine:

- Flight line interval
- Number of flight lines
- Photo point interval along flight lines
- Total number of photographs

Step 1. Determine photographic scale (S) of an image acquired at 10,000 ft AGL with a 28-mm focal length lens\(^1\).

Convert all units of measure to a common scale (feet)

\[
28\text{-mm}/(10\text{-mm/cm}) = 2.8 \text{ cm}/(2.54 \text{ cm/inch})
= 1.10 \text{ inches}/12
= 0.092 \text{ feet}
\]

\[
S = \frac{H - h}{f}
= \frac{10,000}{0.092}
= 108,695.65 \text{ or } 1:108,695
\]

Step 2. Determine interval between flight lines.

Convert CCD chip width dimension from millimeters to feet

\[
\text{Chip width} = \frac{13.7 \text{ mm}}{10}
= 1.37 \text{ cm}/(2.54 \text{ cm/inch})
= 0.54 \text{ inches}/12
= 0.045 \text{ feet}
\]

\[
\text{Chip height} = \frac{9.1 \text{ mm}}{10}
= 0.91 \text{ cm}/(2.54 \text{ cm/inch})
= 0.36 \text{ inches}/12
= 0.030 \text{ feet}
\]

---

\(^1\)Computations for Steps 2, 3, and 4 of the problem described in section 7.2.1.2 and Steps 1, 2, and 4 of this problem are identical. The terms “ground width” and “swath width” are interchangeable, as are “ground length” and “photographic point interval” interchangeable.
Swath width (ground width) = 0.04494 • 108,695
= 4884.75 feet

Since the specified sidelap = 30 percent, then

flight line interval = 4884.75 • (1-0.30)
= 3,419.33 feet

Step 3. Determine the number of flight lines.

Block width = 3.25 miles • 5280 ft/mile
= 17,160 feet
17,160/3,419.33 = 5.018 or 5 flight lines

Step 4. Determine photographic point interval (ground length) along the flight line.

Convert CCD chip height dimension from millimeters to feet.

Chip height = 9.1 mm/10
= 0.91 cm/(2.54 cm/inch)
= 0.36 inches/12
= 0.02985 feet

In tract distance with no overlap = 0.02985 • 108,695
= 3,244.55 feet

Since the specified overlap = 60 percent then,

photographic point interval = 3,244.55 • (1-0.60)
= 1297.82 feet

Step 5. Determine number of photographs on a flight line.

Block length = 4.2 miles • 5,280 ft./mile
= 22,176 feet

Feet between photographs = 22,176 feet/1,297.82
= 17.07 or 17 photographs per flight line

Step 6. Determine total number of photographs required.

5 flight lines • 17 photographs/flight line = 85 photographs
8.2.2. Kodak DCS 460 Digital Camera

A more advanced digital camera, the Kodak DCS 460, contains an array of 2,048 x 3,072 pixels within an 18.4-mm-by-27.6-mm CCD chip. This provides images that cover 4 times the land area of the DCS 420 camera given the same flying height and lens focal length. This system also has superior image quality to the DCS 420 because of an improved interpolation algorithm within the camera. Unfortunately, the cost of this camera system has precluded its widespread use thus far in natural resource applications (Knapp et al. 1998).

8.2.3. Image Processing

Images taken with digital camera systems can be viewed and corrected for exposure and color balance using readily available software, such as Adobe Photoshop.

Because of the relatively small land area coverage of photographic images taken with the DCS 420 camera, mosaicking these images maximizes their utility. Work is currently in progress by FHTET and RSAC to adapt the Airborne Video Toolkit (section 8.1.4) to digital imagery acquired from still cameras via auto-correlation techniques. This involves the use of automated methods to select image-to-image tie points so that image warping calculations can be calculated without need for aircraft altitude information (Linden 1998).
9.0. SATELLITE REMOTE SENSING

On July 23, 1972, Landsat 1, originally named ERTS-1, was launched from Vandenburg Air Force Base in California. The launch of Landsat 1 was the beginning of a new era in monitoring the Earth’s natural resources. Today, acquisition of resource data from Earth-orbiting satellites is commonplace. This chapter discusses the pros and cons of satellite imagery for monitoring and assessment of forest conditions, the characteristics of some of the satellites presently in orbit, and applications in forest health protection.

9.1. STRENGTHS AND WEAKNESSES

Earth-orbiting satellites have the capacity to view and capture large areas of land in a single image, making them an excellent tool for monitoring and assessment of land cover and land use. Another strength of satellites is that they return to the same point over the Earth’s surface at regular intervals (e.g., Landsat 1’s return time or temporal resolution was 16 days). Provided that cloud-free or near-cloud-free weather conditions exist, satellites can obtain data at predictable intervals for monitoring change. The satellite data is received in digital form, ready for computer-assisted analysis, and many Earth-orbiting satellites have spectral sensitivities in the visible, near-IR, and thermal-IR regions of the EMS.

The major weakness of the Earth-orbiting satellites in operation today, especially with regard to forest health protection, is their relatively low spatial resolution. While present day spatial resolutions are adequate for many natural resources applications—such as analysis of land form, land use, crop forecasting, and land cover mapping—they are still unable to resolve the low to moderate levels of forest damage of vital interest to forest health specialists. Consequently, use of data from Earth-orbiting satellites in forest health protection has, to date, been limited to tests and demonstration projects.

9.2. CHARACTERISTICS OF SOME EARTH-ORBITING SATELLITES

The following summary reviews characteristics of a number of satellites in orbit around the Earth today, and is taken primarily from USDA Forest Service (1998a) and Internet web sites for the various satellites.

9.2.1. Advanced Very High Resolution Radiometer

The Advanced Very-High Resolution Radiometer (AVHRR) sensors are managed by the National Oceanic and Atmospheric Administration (NOAA), and have been used since the late 1970s for monitoring weather and ocean temperature. AVHRR imagery can be accessed world-wide at no cost, provided that the user has a station that can receive AVHRR signals as the satellite passes overhead, along with the appropriate data processing software (Figures 9.1 and 9.2). In the U.S., AVHRR imagery is available on a daily basis as individual scenes or as bi-weekly composites of relatively cloud-free scenes for the entire U.S. Spectral resolution includes five bands: one visible (red) band, one near-IR band, and three thermal-IR bands (Table 9.1). Spatial resolution is 1.1 kilometers, temporal resolution is daily, and swath width of the image is 2,400 kilometers. Usually, two NOAA AVHRR satellites are in orbit at any one time.
Figure 9.1. Local Area Remote Sensing (LARS) antenna capable of receiving NOAA AVHRR data, Managua, Nicaragua.

Figure 9.2. An image analyst processes data received from the NOAA-AVHRR satellite in Managua, Nicaragua, for forest fire detection and assessment of vegetation conditions.
Table 9.1. Spectral Resolution of the NOAA AVHRR.

<table>
<thead>
<tr>
<th>Band</th>
<th>Spectral Resolution (µm)</th>
<th>Spectral Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.58 - 0.68</td>
<td>Red</td>
</tr>
<tr>
<td>2</td>
<td>0.72 - 1.10</td>
<td>Near-IR</td>
</tr>
<tr>
<td>3</td>
<td>3.55 - 3.93</td>
<td>Thermal-IR</td>
</tr>
<tr>
<td>4</td>
<td>10.3 - 11.3</td>
<td>Thermal-IR</td>
</tr>
<tr>
<td>5</td>
<td>11.5 - 12.5</td>
<td>Thermal-IR</td>
</tr>
</tbody>
</table>

Applications of AVHRR data include mapping past and present stream channels, measuring surface water temperatures, mapping snow cover, monitoring floods, analysis of soil moisture, fuels mapping (using NDVI), fire detection and mapping, monitoring dust and sand storms, mapping regional drainage patterns and physiographic features, and monitoring volcanic eruptions. There are no applications to date in forest health protection, primarily because of its low (1.1-kilometer) spatial resolution.

9.2.2. Landsat

The Landsat satellites have been acquiring Earth resource data since 1972 and all have been in a polar orbit. Landsats 1, 2, and 3 returned over the same point on the Earth’s surface every 18 days, and Landsats 4, 5, and 7 return over the same point on the Earth’s surface every 16 days. (Landsat 6 was lost in space.)

The early Landsat satellites (Landsats 1-3) were equipped with a four-band multispectral scanner. Spectral resolution consisted of two visible bands and two near-IR bands (Table 9.2). Spatial resolution was 80 m, temporal resolution was 16 or 18 days, and image swath width was 185 kilometers.

Table 9.2. Spectral Resolution of Landsat MSS.

<table>
<thead>
<tr>
<th>Band</th>
<th>Spectral Resolution (µm)</th>
<th>Spectral Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.5-0.6</td>
<td>Green</td>
</tr>
<tr>
<td>5</td>
<td>0.6-0.7</td>
<td>Red</td>
</tr>
<tr>
<td>6</td>
<td>0.7-0.8</td>
<td>Near-IR</td>
</tr>
<tr>
<td>7</td>
<td>0.8-1.1</td>
<td>Near-IR</td>
</tr>
<tr>
<td>8*</td>
<td>10.4 - 12.6</td>
<td>Thermal-IR</td>
</tr>
</tbody>
</table>

*MSS data have been used for land cover classification, change detection, geological investigations, geomorphological mapping, hydrological studies, forest inventory, soil studies, oceanography, and crop yield estimations. In forest health protection, MSS imagery has been used for mapping areas of extensive forest defoliation and tree mortality (section 9.4).
The Landsat Thematic Mapper (TM), first carried aboard Landsats 4, 5, and 7 in addition to the MSS, is a more sophisticated instrument with increased spectral and spatial resolution. The TM has a spectral resolution of seven bands selected specifically for vegetation analysis (Table 9.3). Spatial resolution for all bands except band 6 is 30 meters, while band 6 has a 120-meter resolution. Area covered by a single TM scene is 31,450 square kilometers (185 kilometers by 172 kilometers).

Table 9.3. Spectral Resolution of Landsat TM

<table>
<thead>
<tr>
<th>Band</th>
<th>Spectral Resolution (µm)</th>
<th>Spectral Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45-0.52</td>
<td>Blue</td>
</tr>
<tr>
<td>2</td>
<td>0.52-0.60</td>
<td>Green</td>
</tr>
<tr>
<td>3</td>
<td>0.63-0.69</td>
<td>Red</td>
</tr>
<tr>
<td>4</td>
<td>0.76-0.90</td>
<td>Near-IR</td>
</tr>
<tr>
<td>5</td>
<td>1.55-1.75</td>
<td>Mid-IR</td>
</tr>
<tr>
<td>6</td>
<td>10.4-12.5</td>
<td>Thermal-IR</td>
</tr>
<tr>
<td>7</td>
<td>2.08-2.35</td>
<td>Mid-IR</td>
</tr>
</tbody>
</table>

TM data have been widely used in many disciplines including agriculture, cartography, civil engineering, forestry, geology, geography and land and water resources analysis. Applications in forest health protection include mapping of heavy, widespread damage and change detection.

Landsat 7, which was launched April 1999, has on board an enhanced TM capable of producing panchromatic data with a spatial resolution of 15 meters and a multispectral resolution of 30 meters.

9.2.3. Système Pour l’Observation de la Terre

Spot-1, the first of a series of resource-monitoring satellites operated by SPOT Image, a French Company based in Toulouse, was launched in February 1986. The SPOT satellites are in a phased polar orbit 832 kilometers (500 miles) over the Earth’s surface. They overfly each of 326 ground tracks at an interval of 26 days. SPOTs 1 to 3 carried two high-resolution visible (HRV) pushbroom scanners, each capable of operating in either multispectral or panchromatic mode. Spectral resolution of the multispectral mode consists of three bands (two visible and one near-IR) and one visible band for the panchromatic mode (Table 9.4). Spatial resolution is 20 meters for the multispectral mode and 10 meters for the panchromatic mode. Temporal Resolution is 26 days, and image swath width is 60 kilometers. Land area covered by a single scene is 3,600 square kilometers (60 kilometers by 60 kilometers).
Table 9.4. Spectral Resolution of SPOT

<table>
<thead>
<tr>
<th>Sensor Mode/Band</th>
<th>Spectral Resolution (µm)</th>
<th>Spectral Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multispectral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.50-0.59</td>
<td>Green</td>
</tr>
<tr>
<td>2</td>
<td>0.61-0.68</td>
<td>Red</td>
</tr>
<tr>
<td>3</td>
<td>0.79-0.98</td>
<td>Near-IR</td>
</tr>
<tr>
<td>Panchromatic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.51-0.73</td>
<td>Green-red</td>
</tr>
</tbody>
</table>

SPOT 4, which was launched in 1998, has the same HRV sensor package as did the earlier SPOT satellites plus several additional packages. Of particular interest to individuals concerned with vegetation assessment is the VEGETATION Instrument, a very wide angle (2,250-kilometer-wide swath) Earth-observation instrument, offering a spatial resolution of about 1 kilometer and high radiometric resolution. This instrument uses the same spectral bands as the HRV scanners plus an additional band designated Band 0 (0.43-0.47µ) for oceanographic applications and for atmospheric corrections. The VEGETATION Instrument was developed as a cooperative European project including the European Union, Belgium, France, Italy, and Sweden. VEGETATION operates independently from the HRV scanners, and is designed to provide global coverage on an almost daily basis at a resolution of 1 kilometer for observing long-term environmental changes on a regional and global scale. Data acquired by this instrument is stored in a centralized global archive accessible to users for mapping vegetation cover, forecasting crop yields, and other thematic applications.

Applications of SPOT have been similar to that of Landsat TM. SPOT’s slightly higher spatial resolution, when compared to the Landsat TM, can improve detection of smaller features. In forest health protection, SPOT multispectral imagery has been used for mapping of defoliation by gypsy moth (section 9.4).

9.2.4. Indian Remote Sensing

The Indian Remote Sensing (IRS) satellites IRS-1C and IRS-1D were launched in 1995 and 1996 by India, and have specific applications for vegetation discrimination and land cover mapping. Three sensors are carried on board the IRS-1C and 1D satellites: the Linear Imaging Self-Scanning Sensor (LISS), the Wide Field Sensor (WiFS) and a panchromatic sensor. The LISS-III has a four-band spectral resolution, with two visible and two near-IR bands; the WiFS has two bands, red and near-IR, and the panchromatic sensor has a single visible band (Table 9.5).
Table 9.5. Spectral Resolution of the Indian Remote Sensing Satellite (IRS)

<table>
<thead>
<tr>
<th>Sensor/Band</th>
<th>Spectral Resolution (µm)</th>
<th>Spectral Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>LISS-III</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.52-0.59</td>
<td>Green</td>
</tr>
<tr>
<td>3</td>
<td>0.62-0.68</td>
<td>Red</td>
</tr>
<tr>
<td>4</td>
<td>0.77-0.86</td>
<td>Near-IR</td>
</tr>
<tr>
<td>5</td>
<td>1.55-1.70</td>
<td>Short-wave IR</td>
</tr>
<tr>
<td>Panchromatic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.50-0.75</td>
<td>Green-red</td>
</tr>
<tr>
<td>WiFS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.62-0.68</td>
<td>Red</td>
</tr>
<tr>
<td>2</td>
<td>0.77-0.86</td>
<td>Near-IR</td>
</tr>
</tbody>
</table>

Spatial and temporal resolution and image swath width varies by sensor. The LISS-III has a spatial resolution of 23 meters, except for band 5, which has a 70-meter resolution. Swath width is 142 kilometers. The panchromatic sensor has a spatial resolution of 5 meters, the highest resolution of present day satellite data commercially available at this time and an image swath width of 70 kilometer. WiFS has a spatial resolution of 188 meters and a swath width of 774 kilometers. Both the LISS-III and the panchromatic sensors have temporal resolutions of 24 days, and the WiFS has a temporal resolution of 5 days.

The LISS sensor is comparable to Landsat TM in spatial and spectral resolution, and the WiFS sensor is similar to AVHRR.

9.2.5. RADARSAT

The Canadian space agency launched RADARSAT in 1995 to monitor environmental change and support resource sustainability. RADARSAT carries a synthetic aperture radar (SAR), which is a microwave instrument capable of transmitting and receiving data through clouds, haze, smoke, and darkness. This capability makes radar data a valuable tool for assessing areas that are rarely cloud-free. The swath width of RADARSAT data can range from 35 kilometers (10-meter resolution) to 500 kilometers (100-meter resolution). Applications of RADARSAT and other radar data include monitoring of sea ice for ship navigation, crop monitoring and mapping distribution of forest and snow. Areas of blowdown have also been mapped with this sensor (section 9.4.7).
9.2.6. European Space Agency Satellites

The European space Agency (ESA) operates two Earth-resource satellites (ERS), ERS-1 and ERS-2, which carry several instruments for gathering remotely sensed data. One instrument, an SAR, produces cloud-free radar images. The other instruments collect atmospheric data. ERS data are similar to RADARSAT in that they can be used to assess and monitor vegetation.

9.2.7. Japanese Earth Resources Satellite

The Japanese Earth-Resources Satellite (JERS) acquires data in four multispectral bands and also has a SAR. Bands 3 and 4 of the JERS sense the same portion of the EMS; however, band 4 is forward-looking, thus providing stereoscopic capability.

9.2.8. IKONOS

IKONOS is a high resolution commercial Earth imaging satellite launched in September 1999. The satellite is owned and operated by Space Imaging headquartered near Denver, Colorado, and is considered to be the worlds highest-resolution commercial satellite. IKONOS is in a sun-synchronous polar orbit at an altitude of 681 kilometers (423 miles). A single image captures an area of 11 by 11 kilometers. Spatial resolution is 1 meter in panchromatic mode and 4 meters in multispectral mode. Spectral resolution of the multispectral band is 4 meters, with band sensitivities in the blue, green, red, and near-IR regions of the EMS (Table 9.6). Temporal resolution is given at three days at 1-meter resolution and 1.5 days at 4-meter resolution.

<table>
<thead>
<tr>
<th>Sensor Mode/Band</th>
<th>Spectral Resolution (µm)</th>
<th>Spectral Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multispectral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.45-0.52</td>
<td>Blue</td>
</tr>
<tr>
<td>2</td>
<td>0.52-0.60</td>
<td>Green</td>
</tr>
<tr>
<td>3</td>
<td>0.63-0.69</td>
<td>Red</td>
</tr>
<tr>
<td>4</td>
<td>0.76-0.90</td>
<td>Near-IR</td>
</tr>
<tr>
<td>Panchromatic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.45-0.90</td>
<td>Blue - near-IR</td>
</tr>
</tbody>
</table>

It is anticipated that IKONOS imagery will find applications in precision farming and agriculture, mapping, natural resources management, urban planning and zoning, oil and gas exploration, travel and tourism, etc.
9.3. **PROBABILITY OF DATA CAPTURE**

Assuming that an Earth-orbiting satellite has sufficient spatial resolution to capture information on forest damage, the following additional factors must be considered to ensure successful data capture.

- The satellite must occur over the target site at least once during the specified biowindow.
- There must be cloud-free or near cloud-free conditions when the satellite is over the target area.

The probability of acquiring needed data \( (p^1) \) can be expressed as follows:

\[
p = 1 - p^1
\]

where:

\[
p^1 = (1 - \frac{NCF}{N})^d
\]

and:

- \( NCF \) = Number of cloud free days during the biowindow.
- \( N \) = Total days in the biowindow.
- \( d \) = Number of days the sensor is over the target area.

This relationship was used to compare the probability of acquiring imagery over portions of the mid-Atlantic states during the period of peak defoliation by gypsy moth during 1987 using high-altitude panoramic aerial photographs (chapter 6, section 6.3.3.2; chapter 7, section 7.2.1), Landsat TM, or SPOT imagery (Ciesla and Eav 1987).

**Acquisition biowindow (N)** was defined as follows:

- **Area 1** - June 23-July 5 (south of the Maryland/Pennsylvania line and east of longitude 77°50′) - 12 days.
- **Area 2** - July 1-15 (north of Maryland/Pennsylvania line and west of longitude 77°50′) - 15 days.

**Number of cloud free days (NCF).** Using data from Lee and Johnson (1985), the number of days with less than 10 percent cloud cover for Washington D.C., the approximate center of the target area was determined to be **2.64 days for June** and **2.2 days for July**. Probability of a cloud-free day was assumed to be uniform for each month. In addition, it was assumed that no serial correlation among days existed: that is, the probability of a cloud-free day does not depend on whether or not the previous day was cloud free.
Sensor availability (d). The NASA ER-2 aircraft, when deployed for the gypsy moth photo acquisition mission, was considered to be dedicated to that mission and was available each time a favorable day occurred except for one day when the aircraft was down for repairs. Therefore, for Area 1, the ER-2 was available for 11 days and for Area 2, 14 days.

In 1987, Landsat 5 was over Area 1 for 2 days and Area 2 for 3 days during the defined acquisition window; however, the satellite would pass over each of the four paths required to capture the entire target area only once (Table 9.7).

Table 9.7. Projected dates when Landsat 5 would be over the mid-Atlantic gypsy moth survey area between June 3 and July 15, 1987 (Ciesla and Eav 1987).

<table>
<thead>
<tr>
<th>Biowindow</th>
<th>Orbital Path</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17</td>
</tr>
<tr>
<td>Area 1 (June 23-July 5)</td>
<td>July 1</td>
</tr>
<tr>
<td>Area 2 (July 1-15)</td>
<td>July 1</td>
</tr>
</tbody>
</table>

\(^1\)Too early for Area 2  
\(^2\)Too late for Area 1

For SPOT-1, a scenario was developed that maximized its off-nadir viewing capability. This scenario provided for at least two scanning opportunities per orbital path during the designated biowindow. In 1987, SPOT-1 was in an orbital path capable of acquiring data over Area 1 for five days and Area 2 for eight days during the specified biowindow.

This analysis showed that probability of actually acquiring the data was highest for the NASA ER-2 aircraft, followed by SPOT, followed by Landsat (Table 9.8).

Table 9.8. Probability of suitable data acquisition with alternative remote sensing systems over the 1986 gypsy moth survey area in the mid-Atlantic states (Ciesla and Eav 1987).

<table>
<thead>
<tr>
<th>Remote Sensing System</th>
<th>Acquisition Window</th>
<th>Sensor over Target (days)</th>
<th>Probability of Acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area 1 - June 23 to July 5</td>
<td>Area 2 - July 1 to July 15</td>
<td></td>
</tr>
<tr>
<td>ER-2/Iris II</td>
<td>12</td>
<td>14</td>
<td>0.637</td>
</tr>
<tr>
<td>SPOT - 1</td>
<td>5</td>
<td>8</td>
<td>0.344</td>
</tr>
<tr>
<td>Landsat TM</td>
<td>2</td>
<td>3</td>
<td>0.155</td>
</tr>
</tbody>
</table>
9.4. APPLICATIONS

9.4.1. Detection of Sulfur Dioxide Fume Damage to Forests

One of the first examples of the ability of Landsat MSS (ERTS-1) to record massive forest damage occurred in 1973 when an image was acquired over a site near Wawa, Ontario, Canada, that contained a forested area suffering severe damage from sulfur dioxide (SO$_2$) fumes from an industrial source. The area had previously been mapped by aerial sketchmapping and by ultra-small-scale (1:160,000) CIR aerial photographs (Murtha 1972b) and stratified into four damage zones:

1. **Total kill.** Areas almost devoid of vegetation; rock outcrops and landforms prominent; no observable tree growth.

2. **Heavy kill.** Almost complete mortality of all trees; lesser vegetation predominates and a few scattered, stunted shrubs and rock outcrops are present.

3. **Medium Damage.** High mortality of white birch (greater than 50 percent), no appreciable mortality of other hardwoods or conifers. There is significant leaf discoloration of residual birch. Occasional pockets of dense hardwood sapling growth are present.

4. **Light Injury.** Low birch mortality and some foliar damage present, plus yellowing of the foliage of old growth eastern white pine.

Using the image made from the red band (band 5), three damage strata, total kill, heavy kill, and medium damage could be delineated by interpretation of the gray tones on the black and white image. Interpretation and image enhancement failed to separate the known area of light injury, but it was possible to draw a line around the perimeter of the medium kill zone.

Time required to produce a damage map from aerial sketchmapping was one week, from interpretation of the 1:160,000-scale CIR aerial photographs was 2.5 days, and from interpretation of the Landsat-1 image was 0.5 days. The study concluded that Landsat-1 imagery should provide a simple means of mapping and monitoring large forest areas affected by severe SO$_2$ fume damage (Murtha 1973b). This is one of the few instances where forest damage was mapped from a black-and-white image.

9.4.2. Gypsy Moth Defoliation Mapping

The ability of Landsat MSS to delineate defoliation caused by gypsy moth on a statewide basis was demonstrated by Dottavio and Williams (1983). In this study, change in forest condition was determined from analysis of two Landsat scenes taken over the same areas in central Pennsylvania: one prior to defoliation and one at peak defoliation. A forest/non-forest mask was applied to the scene to eliminate all non-forest areas, and the change in reflectance values over forested areas between the pre- and post-defoliation scenes was used to estimate defoliation.
Visual interpretation of SPOT color composite images was compared to classification of defoliation by gypsy moth on panoramic CIR aerial photographs over a test site in southwestern Pennsylvania and western Maryland using a GIS (Figure 9.3). Approximately 2.5 hours were required to complete interpretation of each of two SPOT color composites, in comparison with 15 8-hour person-days to annotate and interpret 74 panoramic CIR aerial photographs of the same area. Although overall agreement between the two map products was 86 percent, there was considerable disagreement between the two sensors in classification of defoliation intensity ($\kappa = 0.3136$, variance $\kappa = 0.00000157$). The occurrence of areas of scattered tree mortality caused by previous year’s defoliation also could not be reliably separated from current year’s defoliation and was a source of commission error.

This project led to the following conclusions (Ciesla et al. 1989):

- Areas of moderate and heavy defoliation caused by gypsy moth are visible on SPOT color composite images. A range of hues of gray and black are associated with defoliation. Appearance of defoliation is influenced by intensity of defoliation and aspect.

- A number of potential sources of interpretation error exist on SPOT-1 images including talus slopes, conifer stands, fallow fields, and tree mortality. The major source of commission error was tree mortality caused by defoliation in previous years.

- SPOT color composites can be visually interpreted for defoliation in about 5 percent of the time required for interpretation of high-altitude panoramic aerial photographs.

- The general location of defoliated areas can be identified on SPOT color composites. Classification of defoliation intensity is less reliable, however. Visual interpretation of SPOT color composites can provide statewide or regional maps showing defoliation but are less reliable for acquisition of site-specific data, such as may be required for assessment of effects of direct suppression of infestations.
Figure 9.3. Comparison of SPOT-1 color composite image with panoramic CIR aerial photographs in southwestern Pennsylvania. **Upper left** - Portion of SPOT-1 color composite of scene K618-J269 taken 26 June 1986, showing areas of hardwood defoliation by gypsy moth on Wills (1), Evitts (2) and Tussy (3) Mountains near Bedford, Pennsylvania. **Upper right and below** - Defoliation as seen on CIR panoramic aerial photographs of Evitts, Wills and Tussy Mountains (Ciesla et al. 1989).

### 9.4.3. Mapping Cumulative Mortality Caused by Mountain Pine Beetle

In 1981, FPM/MAG initiated a pilot project in cooperation with remote sensing specialists in the School of Forest Resources, North Carolina State University, to determine the feasibility of using Landsat MSS data for classifying cumulative mortality of lodgepole pine caused by an extensive outbreak of mountain pine beetle on the Targhee National Forest, Idaho. Portions of two Ranger Districts, the Ashton and Park Island Districts, were selected as test sites. Average reflectance values in each MSS band were obtained for 29 sample stands, which represented a range of lodgepole pine mortality levels on the Forest. MSS digital data were clustered for each stand, generating a set of spectral signatures for three mortality classes based on percent dead merchantable timber volume:

- **Class 1**: 0 to 34.5 percent
- **Class 2**: 35 to 66.5 percent
- **Class 3**: 67 to 100 percent
These signatures were applied to the MSS digital data for the test site using a minimal-distance multispectral classifier look-up table. This classified each pixel within the study area into one of the three mortality classes. Results of this classification appeared to correspond well to existing ground data. Analysis of the classification of the 29 sample stands showed that 22 out of the 29 stands (76 percent) were classified into their correct mortality class (Table 9.9; Brockhaus et al. 1985).


<table>
<thead>
<tr>
<th>Ground Reference Data (% tree mortality)</th>
<th>0-34.5</th>
<th>35-66.5</th>
<th>67-100</th>
<th>Σ Rows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat MSS Classification (% tree mortality)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-34.5</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>35-66.5</td>
<td>1</td>
<td>14</td>
<td>2</td>
<td>17</td>
</tr>
<tr>
<td>67-100</td>
<td>0</td>
<td>2</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Σ Columns</td>
<td>3</td>
<td>18</td>
<td>8</td>
<td>29</td>
</tr>
</tbody>
</table>

9.4.4. Change Detection–California

In 1996, a five-year change detection (chapter 4, section 4.2.3) monitoring program using Landsat TM data was begun as a cooperative undertaking between the Forest Health Protection staff of the Pacific Southwest Region of the USDA Forest Service and the California Department of Forestry. Objective of this program is to implement a long-term, low-cost, and high-quality monitoring program to identify trends in forest health, assess changes in vegetation distribution and composition, and provide data for updating regional vegetation and fire perimeter maps. This program provides monitoring information across all ownerships and vegetation types in California.

Although the numbers representing acres of detected change have not as yet been verified by an accuracy assessment, correlations are reported to exist between detected changes in broadleaf and conifer forest cover types. Large areas of vegetation cover change, such as those caused by timber harvesting, and wildfires, are most easily detected. However, changes in the forest canopy due to thinning, selective harvest, and tree mortality are also detectable. Sample data derived from this project are shown in Tables 9.10 through 9.12.

Management applications of these data are being studied. These include vegetation map revision, fire-perimeter map updates, and timber harvesting plan evaluation. There is also work in progress to assess the effectiveness of county guidelines for oak management and to estimate levels of conifer mortality on National Forest lands (USDA Forest Service 1998a).
Table 9.10. Acres of detected conifer change by National Forest (USDA Forest Service 1998a).

<table>
<thead>
<tr>
<th>National Forest</th>
<th>Vegetation Decrease</th>
<th>No Vegetation Change</th>
<th>Vegetation Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acres</td>
<td>%</td>
<td>Acres</td>
</tr>
<tr>
<td>Sierra</td>
<td>21,268</td>
<td>2.3</td>
<td>867,694</td>
</tr>
<tr>
<td>Stanislaus</td>
<td>28,300</td>
<td>4.5</td>
<td>517,357</td>
</tr>
<tr>
<td>Sequoia</td>
<td>5,003</td>
<td>0.8</td>
<td>579,765</td>
</tr>
<tr>
<td>Inyo</td>
<td>3,245</td>
<td>0.5</td>
<td>702,518</td>
</tr>
</tbody>
</table>

Table 9.11. Acres of detected change by hardwood cover type (USDA Forest Service 1998a).

<table>
<thead>
<tr>
<th>Hardwood Cover Type</th>
<th>Vegetation Decrease</th>
<th>Vegetation Increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acres</td>
<td>%</td>
</tr>
<tr>
<td>Blue oak woodland</td>
<td>27,173</td>
<td>3.0</td>
</tr>
<tr>
<td>Blue oak/foothill pine</td>
<td>4,957</td>
<td>1.8</td>
</tr>
<tr>
<td>Montane hardwoods</td>
<td>31,766</td>
<td>4.0</td>
</tr>
<tr>
<td>Potential hardwoods</td>
<td>52</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 9.12. Largest identified cause of detected change by county (USDA Forest Service 1998a).

<table>
<thead>
<tr>
<th>County</th>
<th>Cause</th>
<th>Acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calaveras</td>
<td>Wildfire</td>
<td>5,846</td>
</tr>
<tr>
<td>Fresno</td>
<td>Wildfire</td>
<td>3,588</td>
</tr>
<tr>
<td>Kern</td>
<td>Harvest</td>
<td>405</td>
</tr>
<tr>
<td>Madera</td>
<td>Harvest</td>
<td>1,571</td>
</tr>
<tr>
<td>Mariposa</td>
<td>Prescribed fire</td>
<td>1,884</td>
</tr>
<tr>
<td>Tulare</td>
<td>Wildfire</td>
<td>405</td>
</tr>
<tr>
<td>Tuolumne</td>
<td>Wildfire</td>
<td>4,086</td>
</tr>
</tbody>
</table>
While this system provides excellent data on gross levels of change, such as those caused by fire or timber harvesting, it is not capable of producing the detailed information on the status of forest insect and disease pests provided by aerial sketchmap surveys.

**9.4.5. Subpixel Analysis for Detection of Spruce Beetle Damage**

The feasibility of subpixel analysis (chapter 4, section 4.2.4.) of Landsat TM data for mapping of tree mortality by spruce beetle was conducted as a joint USDA Forest Service investigation involving FHTET, the Forest Health Protection staff of the Intermountain Region, RSAC, and the Manti-LaSal National Forest. The test site was on a portion of the Wasatch Plateau on the Manti-LaSal National Forest in east-central Utah. Three dates of imagery were acquired and processed using image subpixel classification software, which is an add-on to the ERDAS Imagine image-processing software. Results were compared with existing aerial sketchmap and ground survey data. The subpixel analysis successfully detected areas of spruce mortality, but could not distinguish between mortality due to spruce beetle and tree mortality caused by other agents (e.g., Douglas-fir beetle, mountain pine beetle, or western balsam bark beetles) (Johnson et al. 1997).

**9.4.6. Mapping Hurricane Impact and Recovery**

A combination of NOAA AVHRR images, transformed into a vegetation biomass indicator using the normalized difference vegetation index was combined with a single-date classification of Landsat TM to map the association between forest type and effects of Hurricane Andrew, which struck Louisiana on 26 August 1992. The target site was the Atchafalaya River Basin, containing two major forest types: mixed-hardwood type and bald cypress-water tupelo type. The effects of the hurricane included a reduction in live biomass, followed by an abnormal increase in new vegetative growth. Damage severity was estimated by comparing the biomass maps made before and immediately (3 days) after the storm event. The rate and magnitude of recovery was estimated by comparing biomass maps immediately after the hurricane strike and 1.5 months after the hurricane strike.

This work corroborated results of earlier damage assessments indicating heaviest damage in mixed hardwood forests and less intense damage in the cypress-tupelo forests. It also identified damage not previously detected, and revealed a spatial pattern of heaviest damage in open forests in close proximity to major river systems.

According to Ramsey et al. (1998), the appeal of this technique is that it makes use of commonly used image-processing systems and a simple method to transfer knowledge gained at one scale (AVHRR) to another scale (Landsat TM) in a way that is useful to resource managers. This relatively uncomplicated approach of combining data from two satellite-based remote sensing systems produced information not available from either system individually.

**9.4.7. Mapping Blowdown with RADARSAT**

RADARSAT fine two-beam mode data, with an eight-meter pixel resolution, was used to document blowdown on 60 riparian leave strips on Vancouver Island, British Columbia, Canada. The 60 leave-strips occur in 35 clearcut units, and ran about 27 kilometers, total. Since 1994, about 30 percent of the total strip length has been decimated by high winds. RADARSAT has the capacity to
image openings (holes) in the leave strips regardless of illumination and weather; the data were acquired mostly at night and during rainstorms. Multi-temporal color-composites make the holes easier to see, since color makes the openings appear to be extensions of the cut block. The openings can be measured with image analysis software (Murtha 1997, Murtha 1998 a, b, and c, and Murtha and Mitchell 1998).
10. SOME INTERNATIONAL APPLICATIONS

Forest health protection is a global concern and is by no means restricted to North American forests. This chapter describes some case histories of the use of remote sensing to monitor and map forest health and forest damage in various regions of the world.

10.1. JARRAH DIEBACK–AUSTRALIA

A dieback of jarrah (Eucalyptus marginata) has been witnessed in Western Australia since 1920 (Newhook and Podger 1972, Jacobs 1979 and Weste and Marks 1987). Symptoms include general crown thinning or decline, foliar wilt, dieback, root necrosis, and tree mortality. In addition to jarrah, dieback and mortality has been found on 59 other plant species representing 34 genera and 13 families indigenous to these forests (Weste and Marks 1987). The dieback is related to the presence of the soil fungus, Phytophthora cinnamomi, which is believed to have been introduced into Western Australia and enters jarrah forests via soil attached to motor vehicles, tools, and the clothing of forest workers.

The rate of spread of this disease can be reduced by restricting entry to areas of substantially healthy but threatened jarrah forest. This required a capacity to detect and map known areas of infection and damage not only in the overstory, but also in the understory. Aerial photography was seen as having the best potential to accomplish this task. The procedures used for photograph acquisition, interpretation, data storage, and retrieval are reviewed by Spencer (1985, 1998).

Early trials conducted by Bradshaw (1974) concluded that:

- Normal color film was superior to CIR for interpreting understory symptoms.
- Scales of 1:3,000 to 1:5,000 were needed to detect and identify dying indicator plants in the understory.
- Photographs taken under a cloud cover (shadowless photography) result in superior images because the absence of shadows provides a better view of the understory, and there are no bright reflections to hamper color differentiation.
- Photography should be acquired in autumn (March-May) to coincide with the period of maximum drought stress. This is the time of year when mortality of indicator plants is most pronounced.

Bradshaw (1979) also concluded that a 70-mm camera system had the most suitable geometry and exposure capability to produce aerial photographs of the required specifications. A major constraint with all of the existing camera systems was that the cloud cover (85 to 100 percent) needed for shadowless photography only occurred during about 10–12 days of the specified biowindow for photograph acquisition. Moreover, for 7 to 10 of these days, the cloud cover was around 500-600 meters (approximately 1,650 to 1,970 feet) above ground, too low for photograph acquisition with a conventional 9-inch camera system.
The jarrah inventory was initially designed as a two-stage sample. The first stage consisted of systematically located 0.125 hectares (0.31-acre) sample plots that were measured and interpreted on 1:1,200 scale color aerial photographs. The second phase was a sub-sample of 10 percent of the first phase plots for measurement on the ground. Aerial photographs were acquired with a fixed-base photography system consisting of two 70-mm cameras attached to each end of a 7.5-meter (approximately 25-foot) boom mounted transversely on a Bell Jet Ranger helicopter. Stereoscopic photographs were obtained by simultaneously exposing film in the two cameras.

More recently, the method of photograph acquisition has changed to reflect the very high priority of this work. The new method uses a 9-inch camera equipped with a 300-millimeter (12-inch) focal-length lens and GPS navigation input. Use of this system is made possible because the survey aircraft is placed on standby whenever there is a possibility of suitable cloud conditions as determined by special weather forecasts (Spencer 1998).
10.2. EUROPEAN WOOD WASP–BRAZIL

The European wood wasp (*Sirex noctilio*) (Hymenoptera: Siricidae) (Figure 10.1) is an insect native to Mediterranean Europe and northern Africa, where it attacks severely weakened and/or dying pines and is not considered a pest. This insect has been accidentally introduced into several countries in the southern hemisphere, including Australia, New Zealand, South Africa, Argentina, Uruguay and Brazil where it has become a major pest of pine plantations. Many species of pines, including *Pinus radiata, P. taeda* and *P. elliottii*, which are widely planted in these countries, are highly sensitive to both the toxic mucus that the attacking female wasps inject into the trees and the fungus *Amylostereum areolatum*, which the insects carry on their bodies and introduce into trees.

Figure 10.1. Female European wood wasp (*Sirex noctilio*) ovipositing on *Pinus taeda*, Santa Catarina State, Brazil.

In places where this insect has been introduced, pine attacked by the European wood wasp are killed. The insect has a preference for overstocked plantations in need of thinning and attacks suppressed trees during the early stages of an infestation. The characteristic signature of *S. noctilio* attack, when viewed aerially, consists of a scattering of fading and dead trees (Figure 10.2). During the earliest stages of an infestation, when attacks are confined to suppressed trees under the main forest canopy, aerial detection is difficult. Moreover, the scattered nature of the tree mortality, coupled with the long emergence and attack period of the insect, which results in different periods of peak crown fading across the overall area of infestation, makes assessment via aerial sketchmapping and/or airborne videography systems difficult (Knapp et al. 1998).
Some International Applications

Remote Sensing for Forest Health Protection

Brazil’s three southernmost states, Rio Grande do Sul, Santa Catarina, and Parana, are home to over 1.1 million hectares (2.7 million acres) of exotic, fast growing pine plantations. These plantations are composed primarily of *Pinus taeda* and *P. elliottii*, and provide raw material for a modern forest products industry that supplies both a domestic and export market, and is a major factor in the local economy. *Sirex noctilio* was first discovered in Rio Grande do Sul State in 1988 (Iede et al. 1988). The insect is believed to have spread into Brazil from previously established infestations in neighboring Uruguay, where it has been known to occur since 1980 (Rebuffo 1990). Presently, the insect is known to be widespread in both Rio Grande do Sul and Santa Catarina States. In 1996, infestations were discovered in Parana State (Disperati et al. 1998).

10.2.1. Digital Camera System

Cooperative work involving specialists from the USDA Forest Service and Brazilian counterparts on the use of remote sensing for assessment of damage caused by *S. noctilio* has been underway since 1992. One of the primary thrusts of this cooperation has involved evaluation of the Kodak DCS 420 CIR digital camera system. Comparisons between oblique CIR digital images and 35-mm color photographs indicate that, at low outbreak levels where there are only a few dead and dying trees per hectare, CIR imagery can enhance the dead and dying trees, facilitating their detection. In areas of moderate to heavy tree mortality, CIR digital images were also superior to 35-mm color photographs for detection of tree mortality. The CIR digital imagery was also useful for determining time of insect attack, information considered vital for determining infestation trends and rate of spread (Knapp et al. 1992).

Work by Disperatti et al. (1998) indicates that any type of aerial photographs could be used to produce a map of damage caused by *S. noctilio* but the CIR digital camera system was clearly superior. In testing satellite capabilities for the same purpose, it was not possible to resolve damage by visual interpretation of a red/green/blue color composite of a Landsat TM scene.

Figure 10.2. Scattered tree mortality in pine plantations is the characteristic signature of *Sirex noctilio* infestation, Santa Catarina State, Brazil.
10.2.2. Aerial Sketchmapping

During October 1998, a demonstration of aerial sketchmapping was conducted over a 3,985-hectare (approximately 9,880-acre) industrial forest farm (fazenda) in Santa Catarina State known to have been infested by *S. noctilio* since 1992. The flight was made in a two-place, high-wing Aero Boero 115 aircraft from a flying height of approximately 1,000 feet above MTE at an airspeed of 90 mph. Each plantation in the fazenda was bounded by roads, firebreaks, or changes in vegetation and could be easily recognized from the air. A single aerial observer classified the tree mortality into three classes:

1. **Light** - No visible mortality or a few dead trees scattered across the plantation.

2. **Moderate** - Numerous single dead trees or small groups of dead trees present in an otherwise uniformly green forest canopy.

3. **Heavy** - Tree mortality has reached a level that the forest canopy has a “salt and pepper” pattern of dead and live trees, and the forest canopy has lost its uniform green appearance.

A 1:20,000-scale plantation map, showing the boundaries of each plantation, was used to record the data. Results were compared with ground survey data for each plantation that classified the levels of tree mortality as follows:

- **Class 1**: 1 to 5 percent infestation.
- **Class 2**: 5.1 to 10 percent infestation.
- **Class 3**: 10.1 to 15 percent infestation.
- **Class 4**: Greater than 15 percent infestation.

The first two damage classes as defined from the ground data were collapsed into a single class and was designated “light damage,” the 10 to 15 percent damage class was designated as “moderate,” and the “greater than 15 percent” class was designated as light. The ground data were than compared with the aerial survey data in 3-by-3 error matrix (chapter 4, section 4.4.2).

Some 57 plantations were classified into one of three damage classes in about one hour of flying time, thus enabling a single observer to classify plantations at the rate of about one/minute. Ground data was available for 41 of the 57 plantations classified from the air. Comparison of aerial survey classifications with ground data shows a 63.4-percent agreement between the two methods (kappa = 0.439, variance of kappa = 0.0129) when compared on the basis of number of plantations classified (Table 10.1). When compared on the basis of land area classified, the results were comparable with a 62.7-percent agreement (kappa = 0.433, variance of kappa = 0.000347) (Table 10.2). Most of the error (six plantations, 220.8 hectares) was the result of plantations with moderate damage being classified as having light damage by the aerial survey. This demonstration indicated that aerial sketchmapping offers a rapid, cost-effective approach for rapid classification of the intensity of infestation by *S. noctilio* in Brazilian pine plantations, provided that a cadre of trained aerial observers are available to conduct the surveys (Ciesla and Disperatti 1998, Ciesla et al. 1999).
Some International Applications ........................ Remote Sensing for Forest Health Protection

Table 10.1. Error matrix of level of damage by *Sirex noctilio* to pine plantations as determined from aerial and ground surveys by number of plantations classified - Fazenda Ponte Alta do Norte Santa Catarina State, Brazil.

<table>
<thead>
<tr>
<th>Ground Survey Data</th>
<th>Aerial Survey Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Light</td>
</tr>
<tr>
<td>Moderate</td>
<td>6</td>
</tr>
<tr>
<td>Heavy</td>
<td>19</td>
</tr>
<tr>
<td>Total</td>
<td>41</td>
</tr>
</tbody>
</table>

Table 10.2. Error matrix of level of damage by *Sirex noctilio* to pine plantations as determined from aerial and ground surveys by area (hectares) of plantations classified, Fazenda Ponte Alta do Norte, Santa Catarina State, Brazil.

<table>
<thead>
<tr>
<th>Ground Survey Data</th>
<th>Aerial Survey Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Light</td>
</tr>
<tr>
<td>Moderate</td>
<td>2</td>
</tr>
<tr>
<td>Heavy</td>
<td>19</td>
</tr>
<tr>
<td>Total</td>
<td>41</td>
</tr>
</tbody>
</table>

The recent discovery of *Sirex noctilio* in Parana State has caused concern among members of the local forestry and natural resource communities. While the locations of industrial forestry plantations are well-documented and can be monitored, there are an unknown number of small, non-industrial pine plantations in the state for which no locational information exists. It is feared that these plantations could become a recurring source of infestation. Consequently, there is interest in using some form of remote sensing to locate these plantations and develop a spatial database to document their locations to facilitate monitoring.
10.3. IMPROVED FOREST PEST DETECTION AND MONITORING—CHINA

Forest health is a major forestry concern in the People’s Republic of China. In 1992, a five-year forest sector development program, consisting of several program elements, was funded by the United Nations Development Program (UNDP). One of the program elements was a project entitled “Detection, Monitoring and Forecasting of Forest Insects and Disease.” This project was based at the Anhui Province Forest Biological Control Center in Hefei (hereafter, the Anhui Center), in east-central China, and addresses two forest health concerns:

1. The indigenous forest defoliator *Dendrolimus punctatus*. This insect causes serious damage to the native *Pinus massoniana* and several exotic pines planted in the central and southern China.

2. Mortality of *Pinus massoniana* caused by the pinewood nematode *Bursaphelenchus xylophilus*. This nematode is indigenous to North America but was probably introduced into China from Japan, where it has also caused widespread mortality of native pines.

This project introduced several remote sensing technologies for forest health monitoring and assessment, including:

- Aerial sketchmapping
- Airborne videography
- CIR digital camera system

In addition, a GIS capability was established at the Anhui Center for processing, storage, and retrieval of data acquired via remote sensing and other methodologies. Technical assistance was provided to this project by FAO, and a partnership was developed with USDA Forest Service to assist in technology transfer of forest health monitoring and assessment methods.

10.3.1. Aerial Sketchmapping

As part of the project funded by UNDP, a team from the Anhui Center received training in basic aerial sketchmapping techniques. This was provided by USDA Forest Service personnel. Operational use of aerial sketchmapping in China was hampered by the availability of suitable aircraft. The only available aircraft was the Antanov AN-2, a Russian-built, bi-wing, 11-place aircraft, used in China primarily for aerial application of pesticides and having limited visibility. Other factors limiting the utility of aerial sketchmapping were areas of restricted airspace and high levels of atmospheric haze, which reduced visibility.
10.3.2. Airborne Videography

Beginning in 1994, the USDA Forest Service began to transfer airborne videography technology to two units engaged in forest insect and disease monitoring in China. These included the Anhui Center, under the UNDP project, and the Chinese Academy of Forestry in Beijing. The primary damage to be mapped was defoliation of pine plantations by the pine caterpillar, *Dendrolimus punctatus*. Damage caused by this pest is not conspicuous until trees are heavily damaged (Wu and Wang 1997). Purpose of this work was to develop a means for monitoring the early stages of damage.

From 1994 to 1996, airborne video imagery was taken over both mature and immature pine forests in the Guangxi Zhuang Autonomous Region and Zhejiang Province. The imagery was processed using MIPS software. Individual videography frames were captured and converted to digital format for processing. The frames were then tiled together to form complete flight lines, which were geographically referenced to an existing topographic map. A contrast enhancement was applied to each band of imagery allowing damage to be easily distinguished and permitting differentiation of healthy and damaged forest lands.

The office sketchmapping technique, on the other hand, proved to be of little value. From the GPS data on the imagery, the general location of infested areas could be determined but could not be used to precisely orient the video image to the map. By using the geographically referenced imagery within the image processing system, image analysts were able to assess defoliation and plot the information onto geo-referenced maps.

Detection threshold for defoliation by pine caterpillar on airborne video imagery appeared to be around 50 percent defoliation. Local forest health specialists were able to classify defoliation into three classes (Frament 1998):

- **Class 1**: Greater than 90 percent defoliation
- **Class 2**: Between 75 and 90 percent defoliation
- **Class 3**: Less than 75 percent defoliation

10.3.3. Digital Camera System

A Kodak DCS-420 CIR digital camera system was acquired by the Anhui Center during the final year of the UNDP funded project. Tests conducted with the system indicated that tree mortality caused by pine caterpillar defoliation could be more easily identified on the digital images than via visible observation or color photographs. The CIR images produced by this camera provided increased contrast between live, dead, and dying trees.

Because of lack of availability of suitable aircraft and restricted airspace, personnel of the Anhui Center are presently using the DCS-420 camera to capture forest damage from fire lookouts and other pre-established GPS reference points. Resultant information is processed, interpreted and manually transferred into a GIS (Knapp et al. 1998).
10.4. FOREST DECLINE—GERMANY

Beginning in the late 1970s, a regional decline of both conifers and broadleaf trees occurred in the forests of central Europe, especially in Germany. The decline received a great deal of public attention by the scientific community, political leaders, and the general public.

A wide range of symptoms occurred on various species. On Norway spruce, the predominant symptoms were a chlorosis or yellowing of the older foliage and crown thinning (Figure 10.3). On silver fir (Abies alba), symptoms included a sudden reduction in height growth (resulting in a flattened crown that resembles a stork’s nest) and branch dieback (Figure 10.3)\(^1\). On other species, symptoms included crown thinning, radial growth reduction, loss of feeder roots, and abnormally heavy seed crops. In Germany, this condition was first referred to as Waldsterben (forest death) and later as neuartige Waldschäden (a new type of forest damage). Many reviews of this condition appear in the literature, and there was concern that this decline was the result of deposition of toxic, nutrient, acidifying, and/or growth altering substances from human sources (Schutt and Cowling 1985, Niesslein and Voss 1985, Plochman 1985, Steinbeck 1984).

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\(^1\) The stork’s-nest symptom on Abies alba has actually been reported in the literature since the early 1800s in Germany and other European countries (Ruzicka 1937).
The concern about *neuartige Waldschäden* and the future of Europe’s forests prompted the initiation of annual surveys to assess forest condition. These were begun in Germany in 1983, and are now conducted in most western European countries. The basic design involves classifying trees on permanent plots established on a 4-by-4-kilometer grid into one of five standardized, generic damage classes based on defoliation and foliar discoloration (Tables 10.3 and 10.4). Classification is done by ground observation.

Table 10.3. European forest-tree damage-rating system based on degree of defoliation (Commission of European Communities 1991).

<table>
<thead>
<tr>
<th>Damage Class</th>
<th>Degree of Defoliation</th>
<th>Needle/leaf Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Not defoliated</td>
<td>0-10%</td>
</tr>
<tr>
<td>1</td>
<td>Slightly defoliated</td>
<td>11-25%</td>
</tr>
<tr>
<td>2</td>
<td>Moderately defoliated</td>
<td>26-60%</td>
</tr>
<tr>
<td>3</td>
<td>Severely defoliated</td>
<td>&gt;60%</td>
</tr>
<tr>
<td>4</td>
<td>Dead</td>
<td></td>
</tr>
</tbody>
</table>

Table 10.4. European forest-tree damage-rating system based on degree of foliage discoloration (Commission of European Communities 1991).

<table>
<thead>
<tr>
<th>Damage Class</th>
<th>Degree of Discoloration</th>
<th>Discoloration (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Not discolored</td>
<td>0-10%</td>
</tr>
<tr>
<td>1</td>
<td>Slightly discolored</td>
<td>11-25%</td>
</tr>
<tr>
<td>2</td>
<td>Moderately discolored</td>
<td>26-60%</td>
</tr>
<tr>
<td>3</td>
<td>Severely discolored</td>
<td>&gt;60%</td>
</tr>
<tr>
<td>4</td>
<td>Dead</td>
<td></td>
</tr>
</tbody>
</table>

In addition to the ground surveys of forest decline, assessments using remote sensing were also conducted. These included use of CIR aerial photographs, airborne multi-spectral scanners and Landsat TM. A review of the remote sensing approaches used in the former West Germany for assessment of forest decline was prepared by Ciesla and Hildebrandt (1986).

CIR aerial photographs were widely used in several former West German states for forest damage assessment. Photography missions were flown by commercial contractors with 9-inch mapping cameras equipped with 12-inch focal-length lenses in midsummer. The most frequently used photographic scales were 1:5,000 and 1:6,000 (Hildebrandt and Kadro 1984, Hildebrandt, 1985). Air photointerpretation involved examination of individual trees crowns and classification of tree species and tree condition using the same damage classes developed for the ground surveys. The forests of central Europe have relatively few tree species, and most have unique crown signatures.
that allow them to be identified based on the characteristics described in chapter 3, section 3.2.2. Photointerpretation keys, including both narrative descriptions and illustrations for each tree species and damage classes, were developed for major commercial tree species in various German states (Grundmann 1984, Hartmann 1984, Runkel and Roloff 1985) (Figure 10.4).

![Figure 10.4. Section of a CIR aerial photograph from Germany’s Black Forest region showing trees in various stages of decline. Original photographic scale = 1:5,000 (original aerial photography made available by Dr. G. Hildebrandt, retired, Department of Photo Interpretation and Remote Sensing, University of Freiburg, Freiburg im Breisgau, Germany).](image)

The following description of an assessment of forest decline using CIR aerial photographs conducted in the German state of Baden-Württemberg during 1983 (Hildebrandt and Kadro 1984) serves as an example of how these assessments were conducted:

“North-south flight lines, spaced at 8-km intervals were flown with CIR film at a photographic scale of 1:5,000 during late July. Flight lines coincided with the country-wide Gauss-Kruger survey grid. Aerial photographs along each flight line were flown with a standard 60 percent overlap. Areas with less than 10 percent forest cover were deleted from the flight plan. Aerial photographic plots were established on every third photograph along the flight line. These were located by placing a clear plastic overlay, marked with a series of circular plots, over the sample photograph. Sample trees occurring closest to plot center were identified by species and rated for degree of decline. Six sample plots of 20 trees each were classified on each photograph. Additional data taken at each plot location were:
1. Elevation (from topographic maps)
2. Slope and aspect
3. Topographic position
4. Age class and stand density
5. Forest type
6. Location of plot within stand (edge, middle, adjacent to opening, etc.)

Other remote sensing approaches evaluated for ability to resolve and classify decline symptoms included a test of a Bendix M2S airborne multispectral scanner and Landsat TM imagery. While these systems showed some ability to resolve damage, most German foresters and remote sensing specialists agreed that CIR film was the most suitable tool for damage assessment via remote sensing (Hildebrandt and Kadro 1984, Kadro 1984).
10.5. CYPRESS APHID–KENYA

The cypress aphid (Cinara cupressi) (Figure 10.5), a major pest of various species of cypress (Cupressus spp.), appeared in Malawi in 1986 (Odera 1991) and gradually spread across portions of eastern and southern Africa, where the cypress Cupressus lusitanica is widely planted both as an ornamental and as an industrial forest species. Feeding by aphid colonies causes a dessication of the foliage during dry seasons, and can cause extensive tree mortality (Figure 10.6). The insect appeared in Kenya in 1990, and by the time the first infestations were discovered, it was established throughout all of the country’s cypress plantations. The introduction of this insect into Kenya was particularly devastating because some 46 percent of the country’s industrial forest plantations are composed of cypress and harvesting of wood products from most natural forests has been banned (Ciesla et al. 1995).

Figure 10.5. Colony of cypress aphid near Muguga, Kenya.
Figure 10.6. Feeding injury to cypress caused by cypress aphid, Nairobi, Kenya.

Shortly after the discovery of cypress aphid in Kenya, emergency funding was provided by FAO to begin a pest management program directed against this insect. This was followed by a longer term project funded by UNDP and the World Bank. As part of this effort, an aerial sketchmapping program was initiated to map plantations with extensive tree mortality so that salvage operations could be conducted (Figures 10.7 and 10.8). Aircraft suitable for aerial sketchmapping are readily available in Kenya, being used for tourist-related activities, wildlife census, and flying doctor programs. A team of aerial observers was trained, and the first country-wide aerial and ground survey of Kenya’s forest plantations was completed in February 1992 (Ward 1992, Ward et al. 1992). With the help of specialists from the USDA Forest Service, resulting data were digitized into a PC version of the GIS ARC-INFO (Ciesla et al. 1995).
Figure 10.7. An aerial observer briefs a pilot on survey mission requirements prior to an aerial sketchmap survey of cypress aphid infestations in Kenya.

Figure 10.8. Aerial view of tree mortality (gray cast) in cypress (*Cupressus lusitanica*) plantations caused by cypress aphid near Eldoret, Kenya.
10.6. **OZONE DAMAGE TO FORESTS–MEXICO**

Beginning in 1981, decline and mortality of sacred fir (*Abies religiosa*) was discovered in the Parque Nacional Desierto de los Leones, near Mexico City. This species occurs in pure stands between elevations of 9,000 and 10,000 feet in central Mexico. Symptoms of the decline included discoloration of foliage, loss of older foliage, reduced growth, dead branches, and lack of cone crops (Figure 10.9). The decline was followed by extensive tree mortality due to infestations of two species of bark beetles *Pseudohylesinus variegatus* and *Scolytus mundos*. Forests of *Pinus hartwegii*, which grow in pure stands at elevations above the fir forests, displayed a yellow flecking on the foliage characteristic of elevated ozone levels. Decline of both the fir and pine was attributed to ozone, which is produced when pollutant-laden air trapped in the Mexico City basin is exposed to sunlight. High levels of ozone were measured in the basin, and street trees and vegetable crops in Mexico City also showed classic symptoms of ozone damage at the time the forest damage was discovered (Bauer and Krupa 1990, Cibrion Tovar 1989, Ciesla and Macias Samano 1997).

![Figure 10.9. Declining *Abies religiosa*, Parque Nacional Desierto de los Leones near Mexico City.](image)
During 1985, foresters and forest protection specialists from the Secretaria Agricolas y Recursos Hidraulicos (SARH) in Mexico City acquired 9-inch CIR aerial photographs over the affected areas at a scale of 1:10,000. These were used to help map the vegetation communities in the park and classify them into damage strata. A second set of photographs was taken in 1987 to monitor and document the spread and intensification of the damage and help plan timber salvage operations (Ciesla and Macias Samano 1989).

The CIR photographs were processed to a negative and paper prints were produced for photointerpretation and field use (Figure 10.10). This procedure altered the color balance of the photographs and resulted in a less-than-optimum product. Tree mortality in the park was so intense, however, that it was resolved on the photographs, and could be classified and mapped by photointerpreters.

Figure 10.10. Foresters and forest health specialists use CIR photographic prints to aid in ground surveys in Parque Nacional Desierto de Los Leones near Mexico City.
10.7. DECLINE OF RIVERINE FORESTS—SUDAN

Sunt (*Acacia nilotica*) is the most valuable timber producing species in the northern Sudan. The wood is used for railroad ties, structural lumber, fuel wood, and other purposes. *A. nilotica* occurs in pure, even-age stands that have been artificially regenerated by direct seeding in flood plains and remnants of oxbow lakes along major rivers.

Dieback or decline of *A. nilotica* was reported as early as the 1930s, and was initially attributed to infestations of a cambium- and wood-boring beetle, *Sphenoptera chalcicroa arenosa* (Coleoptera: Buprestidae). During the 1980s, extensive decline was detected in *A. nilotica* plantations in oxbow lake beds along the Blue Nile.

An assessment of the decline was made by FAO in 1993 (Ciesla 1993). The first phase of the assessment was an aerial sketchmap survey of the 41 *Acacia nilotica* forests that occur along the Blue Nile between Sennar Reservoir and El Roseires Dam. The survey was made from a twin-engine, overhead-wing Islander aircraft from an altitude of approximately 1,000 feet AGL. Areas of decline were mapped on a 1:250,000-scale, hand-drafted map prepared through the assistance of the Canadian International Development Agency (CIDA) as part of another international development project. This was the only map product available for the area, and while it had relatively little detail, it showed the location of each forest and permitted reasonably accurate pinpointing of decline areas. The areas of decline were easily seen from the air and appeared as patches of trees with thin crowns (Figures 10.11 and 10.12). The map produced from the aerial survey provided a base from which to select sites for ground examination.

The evaluation indicated that the decline was a complex condition probably caused by a series of predisposing, inciting, and contributing factors (Manion 1991). Senescence of even-age stands and silt deposition from annual floods were identified as possible predisposing factors. A catastrophic flood in 1988, which deposited up to 2 meters (approximately 6 feet) of silt in the plantations, insect defoliation, and drought were identified as possible inciting factors, and the occurrence of wood-boring insects was regarded as a secondary or contributing factor (Ciesla 1993).

A special aerial photography mission was subsequently flown over the plantations in 1995 for detailed mapping of decline areas. Nine-inch format color print film was flown at a scale of 1:10,000 over each plantation by a mapping contractor based in Khartoum. Since this was the first color aerial photography mission flown by the contractor, and panchromatic (black and white) aerial films are always exposed through a medium yellow (minus-blue) filter for haze penetration, the contractor neglected to remove the yellow filter prior to photograph acquisition. This resulted in color prints with a yellow cast. It was possible, however, to adjust the color balance of the prints with proper filtration, and produce an end product with an acceptable color balance.
Figure 10.11. Aerial view of decline of *Acacia nilotica* in a forest adjacent to the Blue Nile, Sudan.

Figure 10.12. Ground view of a stand of *Acacia nilotica* with severe decline symptoms, Blue Nile Basin, Sudan.
11. CONCLUSIONS

Remote sensing is an integral and essential tool for collection of data needed to support decisions and action programs to improve forest health. While not all attempts to use remote sensing in forest health protection have proven successful, many have been shown to meet data requirements, and have proven to be cost-effective alternatives to ground data acquisition. Moreover, remote sensing tools have been an integral part of the forest health protection specialist’s tool kit for many years. Aerial sketchmapping, for example, has been an operational system for gathering data on the status of certain forest insects and diseases for over 50 years. Color and CIR aerial photographs have been in use for more than 30 years.

At least two aspects of remote sensing in forest health protection are somewhat unique, regardless of the sensor system used, when compared to other natural resource applications. Forest damage, the subject of greatest interest to forest health protection specialists, usually appears as a change of color of all or a portion of the tree crown. Therefore, color, CIR, or multispectral images are needed to resolve damage, as opposed to black-and-white panchromatic images. Another aspect is the relatively rigid timing requirements (biowindows) for data acquisition dictated by the life cycles of damaging agents (insects, fungi, etc.) and the appearance of peak damage. The same principle applies to noxious weeds, whose signatures may be more detectable during certain times of the year, such as peak flowering and/or fall coloring. These factors, in addition to image resolution, area to be covered, data requirements, and related factors must be given careful consideration when planning remote sensing missions with a forest health protection objective.

At the present time, there are five classes of remote sensing tools that have been shown to be least partially effective in meeting at least some forest health protection data requirements: aerial sketchmapping, aerial photography, airborne videography, digital camera systems and Earth-orbiting satellite imagery. Each have their individual strengths and weaknesses, and all should be considered a collective set of tools available to the forest health specialist (Table 11.1).

Aerial sketchmapping is a low-cost, highly flexible method for data collection, but the resultant data are subjective and their reliability is difficult to assess. Aerial photographs provide a high-resolution product from which data can be extracted in the comfort of an office. They also provide a permanent record of forest conditions at a certain point in time. Aerial photographs are more expensive to acquire than aerial sketchmapping, however, and in some areas, photograph acquisition is hampered by unsuitable weather.

Airborne videography is a tool that provides some of the flexibility and low cost of aerial sketchmapping while also providing a permanent record of forest conditions at a given point in time. Moreover, analog videography images, such as those acquired by the Panasonic CLE 300, are easily converted to digital format for image analysis, and the newer digital videography systems provide data that need not be converted. On the negative side, video imagery has a lower resolution than aerial photographs, making it more difficult to assess subtle damage symptoms or make individual tree counts of dead and dying trees, a procedure done on aerial photographs with relative ease.
Table 11.1. Comparison of alternative remote sensing systems for acquisition data of importance in forest health protection.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Sensor Type</th>
<th>Aerial Sketchmapping</th>
<th>Aerial Photographs (all formats)</th>
<th>Airborne Videography (e.g. Panasonic CLE 300)</th>
<th>Digital Camera (Kodak DCS 420)</th>
<th>Earth-Orbiting Satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition cost</td>
<td>Low</td>
<td>Medium to high</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Medium to low</td>
</tr>
<tr>
<td>Spatial resolution</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
</tr>
<tr>
<td>Spectral range</td>
<td>Visible</td>
<td>Visible; Near-IR</td>
<td>Visible; Near-IR (some systems)</td>
<td>Visible; Near-IR</td>
<td>Visible; Near-IR</td>
<td>Visible; Near-, mid-, thermal-IR; Microwave</td>
</tr>
<tr>
<td>Temporal resolution</td>
<td>User- and weather-defined</td>
<td>User- and weather-defined</td>
<td>User- and weather-defined</td>
<td>User- and weather-defined</td>
<td>1 - 26 days, depending on satellite used.</td>
<td></td>
</tr>
<tr>
<td>Reliability of data</td>
<td>Difficult to measure</td>
<td>High</td>
<td>High</td>
<td>Undetermined</td>
<td>Medium to low</td>
<td></td>
</tr>
<tr>
<td>Probability of acquisition</td>
<td>High</td>
<td>Variable, depending on location</td>
<td>High</td>
<td>Medium to high</td>
<td>Low</td>
<td></td>
</tr>
<tr>
<td>during specified biowindow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data in digital format</td>
<td>Digital data capability is under development</td>
<td>Analog data can be converted to digital</td>
<td>Both analog and digital systems available</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Currently operational</td>
<td>Yes - widely used</td>
<td>Yes - on a project basis</td>
<td>Yes - on a project basis</td>
<td>Under development</td>
<td>Under development</td>
<td></td>
</tr>
</tbody>
</table>
Digital camera systems provide a higher resolution product than do airborne video cameras, and at a relatively low acquisition cost. The Kodak DCS 420 digital camera, for example, can produce a CIR image that approaches the quality of a CIR aerial photograph. The ultra-small format of the currently available digital images, approximately 1/7 the size of a 35-mm photograph, produces images that cover small areas of land, a distinct disadvantage when acquiring imagery over remote, inaccessible forest regions even with the availability of a GPS interface.

Earth-orbiting satellites (NOAA AVHRR, Landsat, SPOT, etc.) offer the advantage of image acquisition at regular intervals, provided that the targets of interest are not under cloud cover. They also provide a range of spectral sensitivity across the EMS. Satellite sensors have a poor spatial resolution, however, when compared to airborne sensors. This currently limits their ability to resolve all but the most severe of forest damage signatures.

The capabilities of the various sensor systems presently available to the forest health protection specialist are a key factor in the type of sensor selected for a specific application (Table 11.2). Aerial sketchmapping, for example, is an excellent tool for damage detection or general damage mapping, but it is not suitable for estimating pest losses or assessments of forest health, stand hazard, or treatment effects. Aerial photographs, on the other hand, are an excellent tool for damage inventories and several other applications, but because of the higher acquisition cost, are not cost-effective for damage detection. Some of the newer systems, such as airborne videography and the Kodak DCS 420 digital camera system, currently have limited operational applications, but could find a wider range of uses with continued testing and evaluation. The relatively low spatial resolution of today’s Earth-orbiting satellites limits their ability to resolve all but the most severe and widespread damage.

Remote sensing is a dynamic technology. New and improved methods of data collection, with superior resolution, are continuously becoming available. Supporting technologies (such as computers with increased data handling and storage capacity), navigation systems (such as GPS), and GIS continue to make data collection via remote sensing increasingly user-friendly and attractive. An example of how these supporting technologies can influence data acquisition by remote sensing is the electronic enhancements to aerial sketchmapping, which incorporate the latest computer hardware, software, and GPS to produce a product that can be entered directly into a GIS.

Perhaps the greatest challenge to forest health protection specialists interested in making full use of the data acquisition opportunities that remote sensing provides is to keep abreast of new technologies as they become available and to evaluate them for specific applications. However, as these technologies are evaluated, it is essential to keep the data requirements to support forest health protection activities in the forefront, and to evaluate new and emerging technologies in light of these requirements.
Table 11.2. Uses of alternative remote sensing systems for acquisition of data of importance in forest health protection.

<table>
<thead>
<tr>
<th>Application</th>
<th>Sensor Type</th>
<th>Aerial Photographs</th>
<th>Airborne Video</th>
<th>Digital Camera</th>
<th>Earth-Orbiting Satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Aerial Sketch-mapping</td>
<td>Small format</td>
<td>Standard format</td>
<td>Large format</td>
</tr>
<tr>
<td>Damage detection</td>
<td>Operational</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Damage mapping and estimation of area affected</td>
<td>Operational</td>
<td></td>
<td></td>
<td>Operational</td>
<td></td>
</tr>
<tr>
<td>Inventories(^2)</td>
<td>Stratification</td>
<td>Operational</td>
<td>Operational</td>
<td>Operational</td>
<td></td>
</tr>
<tr>
<td>Counts of symptomatic trees</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest health assessments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tree species identification</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stand hazard rating</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planning and executing forest health protection activities</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assessment of treatment effects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\)Earth orbiting satellites are only capable of mapping areas of severe and widespread damage or cumulative tree mortality.
\(^2\)Aerial sketchmapping, aerial photographs and ground surveys have been used in multistage sampling systems to acquire data on numbers of trees and associated volume affected by a damaging agent.
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## GLOSSARIES

### ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>alternating current</td>
</tr>
<tr>
<td>AGL</td>
<td>above ground level</td>
</tr>
<tr>
<td>ASPRS</td>
<td>American Society of Photogrammetry and Remote Sensing</td>
</tr>
<tr>
<td>AVHRR</td>
<td>Advanced High Resolution Radiometer</td>
</tr>
<tr>
<td>AVT</td>
<td>airborne videographic toolkit</td>
</tr>
<tr>
<td>BAF</td>
<td>basal area factor</td>
</tr>
<tr>
<td>BLM</td>
<td>Bureau of Land Management</td>
</tr>
<tr>
<td>CCD</td>
<td>charged coupled device</td>
</tr>
<tr>
<td>CIDA</td>
<td>Canadian International Development Agency</td>
</tr>
<tr>
<td>CIR</td>
<td>color infrared</td>
</tr>
<tr>
<td>CSU</td>
<td>Colorado State University</td>
</tr>
<tr>
<td>DBH</td>
<td>diameter at breast height</td>
</tr>
<tr>
<td>DC</td>
<td>direct current</td>
</tr>
<tr>
<td>DF</td>
<td>degrees of freedom</td>
</tr>
<tr>
<td>DMA</td>
<td>Defense Mapping Agency</td>
</tr>
<tr>
<td>DOD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>DRG</td>
<td>Digital Raster Graphics</td>
</tr>
<tr>
<td>EA</td>
<td>Environmental Analysis</td>
</tr>
<tr>
<td>EIS</td>
<td>Environmental Impact Statement</td>
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<tr>
<td>EMS</td>
<td>electromagnetic spectrum</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>ER-2</td>
<td>Earth Resources-2, a civilian version of the U-2 aircraft</td>
</tr>
<tr>
<td>ERS</td>
<td>Earth Resources Satellite (European Space Agency)</td>
</tr>
<tr>
<td>ERTS-1</td>
<td>Earth Resources Telemetry Satellite (Landsat-1)</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>ESRI</td>
<td>Environmental Systems Research Institute</td>
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<tr>
<td>F</td>
<td>Fahrenheit</td>
</tr>
<tr>
<td>FAA</td>
<td>Federal Aviation Administration</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organization of the United Nations</td>
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<tr>
<td>FHTET</td>
<td>Forest Health Technology Enterprise Team</td>
</tr>
<tr>
<td>FPM/MAG</td>
<td>Forest Pest Management/Methods Application Group, now part of the FHTET</td>
</tr>
<tr>
<td>GIS</td>
<td>geographic information system</td>
</tr>
<tr>
<td>GPS</td>
<td>global positioning system</td>
</tr>
<tr>
<td>ha</td>
<td>hectare(s)</td>
</tr>
<tr>
<td>HP</td>
<td>horsepower</td>
</tr>
<tr>
<td>IR</td>
<td>infrared</td>
</tr>
<tr>
<td>IRS</td>
<td>Indian Remote Sensing (Satellite)</td>
</tr>
<tr>
<td>JERS</td>
<td>Japanese Earth Resources Satellite</td>
</tr>
<tr>
<td>km</td>
<td>kilometer(s)</td>
</tr>
<tr>
<td>LANDSAT</td>
<td>a system of Earth-orbiting imaging satellites</td>
</tr>
<tr>
<td>Acronym</td>
<td>Definition</td>
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<td>---------</td>
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</tr>
<tr>
<td>LARS</td>
<td>local-area remote sensing</td>
</tr>
<tr>
<td>LISS</td>
<td>Linear Imaging Self-Scanning Sensor</td>
</tr>
<tr>
<td>m</td>
<td>meter(s)</td>
</tr>
<tr>
<td>MB</td>
<td>megabyte(s)</td>
</tr>
<tr>
<td>MeGIS</td>
<td>Maine Geographic Information System</td>
</tr>
<tr>
<td>MHz</td>
<td>megahertz</td>
</tr>
<tr>
<td>MIPS</td>
<td>Map Image Processing System</td>
</tr>
<tr>
<td>µm</td>
<td>micrometers</td>
</tr>
<tr>
<td>mm</td>
<td>millimeter(s)</td>
</tr>
<tr>
<td>MPH</td>
<td>miles per hour</td>
</tr>
<tr>
<td>MS</td>
<td>mean square</td>
</tr>
<tr>
<td>MSL</td>
<td>mean sea level</td>
</tr>
<tr>
<td>MSS</td>
<td>multispectral scanner</td>
</tr>
<tr>
<td>MTE</td>
<td>mean terrain elevation</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NDVI</td>
<td>normalized difference vegetation index</td>
</tr>
<tr>
<td>NFAP</td>
<td>Nationwide Forestry Applications Program (now, RSAC)</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>NPV</td>
<td>Nuclear polyhedrosis virus</td>
</tr>
<tr>
<td>PC</td>
<td>personal computer</td>
</tr>
<tr>
<td>PCMCIA</td>
<td>Personal Computer Memory Card International Association</td>
</tr>
<tr>
<td>PI</td>
<td>photointerpretation</td>
</tr>
<tr>
<td>PPS</td>
<td>probability proportional to size</td>
</tr>
<tr>
<td>PR</td>
<td>pixel resolution</td>
</tr>
<tr>
<td>PSU</td>
<td>primary sampling unit</td>
</tr>
<tr>
<td>RAM</td>
<td>random access memory</td>
</tr>
<tr>
<td>RSAC</td>
<td>Remote Sensing Applications Center</td>
</tr>
<tr>
<td>SAR</td>
<td>synthetic aperture radar</td>
</tr>
<tr>
<td>SARH</td>
<td>Secretaria Agricola y Recursos Hidraulicos (Mexico)</td>
</tr>
<tr>
<td>SE</td>
<td>standard error</td>
</tr>
<tr>
<td>SMPTE</td>
<td>Society of Motion Picture and Television Engineers</td>
</tr>
<tr>
<td>SPOT</td>
<td>Système Pour l’Observation de la Terre</td>
</tr>
<tr>
<td>SS</td>
<td>sum of square</td>
</tr>
<tr>
<td>SSU</td>
<td>secondary sampling unit</td>
</tr>
<tr>
<td>STOL</td>
<td>short takeoff and landing</td>
</tr>
<tr>
<td>S&amp;PF</td>
<td>State and Private Forestry</td>
</tr>
<tr>
<td>S-VHS</td>
<td>Super-videographic home system</td>
</tr>
<tr>
<td>TM</td>
<td>thematic mapper</td>
</tr>
<tr>
<td>TSU</td>
<td>tertiary sampling unit</td>
</tr>
<tr>
<td>UNDP</td>
<td>United Nations Development Program</td>
</tr>
<tr>
<td>USDA</td>
<td>United States Department of Agriculture</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>WiFS</td>
<td>wide field sensor</td>
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</tbody>
</table>
### COMMON AND SCIENTIFIC NAMES

**Common/Scientific Names: Plant Species**

<table>
<thead>
<tr>
<th>Common Name</th>
<th>Scientific Name</th>
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<tbody>
<tr>
<td>American beech</td>
<td><em>Fagus grandiflora</em></td>
</tr>
<tr>
<td>arborvitae</td>
<td><em>Thuja</em> spp.</td>
</tr>
<tr>
<td>bald cypress</td>
<td><em>Taxodium distichum</em></td>
</tr>
<tr>
<td>balsam fir</td>
<td><em>Abies balsamea</em></td>
</tr>
<tr>
<td>birches</td>
<td><em>Betula</em> spp.</td>
</tr>
<tr>
<td>black locust</td>
<td><em>Robinia pseudoacacia</em></td>
</tr>
<tr>
<td>black pine</td>
<td><em>Pinus mariana</em></td>
</tr>
<tr>
<td>black spruce</td>
<td><em>Picea mariana</em></td>
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<tr>
<td>blue spruce</td>
<td><em>Picea pungens</em></td>
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<tr>
<td>cypress</td>
<td><em>Cupressus</em> spp.</td>
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<tr>
<td>Douglas-fir</td>
<td><em>Pseudotsuga menziesii</em></td>
</tr>
<tr>
<td>eastern larch</td>
<td><em>Larix laricina</em></td>
</tr>
<tr>
<td>eastern white pine</td>
<td><em>Pinus strobus</em></td>
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<td>Engelmann spruce</td>
<td><em>Picea engelmannii</em></td>
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<td>false cypress</td>
<td><em>Chamaecyparis</em> spp.</td>
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<td>Fraser fir</td>
<td><em>Abies fraseri</em></td>
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<tr>
<td>grand fir</td>
<td><em>Abies grandis</em></td>
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<td>Hartweg pine</td>
<td><em>Pinus hartwegii</em></td>
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<td>hemlocks</td>
<td><em>Tsuga</em> spp.</td>
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<td>jack pine</td>
<td><em>Pinus banksiana</em></td>
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<tr>
<td>jarrah</td>
<td><em>Eucalyptus marginata</em></td>
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<tr>
<td>leafy spurge</td>
<td><em>Euphorbia esula</em></td>
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<tr>
<td>loblolly pine</td>
<td><em>Pinus taeda</em></td>
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<tr>
<td>lodgepole pine</td>
<td><em>Pinus contorta</em></td>
</tr>
<tr>
<td>Masson pine</td>
<td><em>Pinus massoniana</em></td>
</tr>
<tr>
<td>melaleuca</td>
<td><em>Melaleuca quinquenervra</em></td>
</tr>
<tr>
<td>Mexican cypress</td>
<td><em>Cupressus lusitanica</em></td>
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<td>Port-Orford cedar</td>
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<td><em>Acer rubrum</em></td>
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<td>red spruce</td>
<td><em>Picea rubens</em></td>
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<td>sacred fir</td>
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<td>shortleaf pine</td>
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## Glossaries

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<td><em>Centaurea maculosa</em></td>
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<tr>
<td>spruce</td>
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</tr>
<tr>
<td>subalpine fir</td>
<td><em>Abies lacicocarpa</em></td>
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<tr>
<td>sugar maple</td>
<td><em>Acer saccharum</em></td>
</tr>
<tr>
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<td><em>Pinus lambertianna</em></td>
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<tr>
<td>sunt</td>
<td><em>Acacia nitolica</em></td>
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<td>Texas lantana</td>
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<tr>
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<td><em>Tsuga heterophylla</em></td>
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<tr>
<td>western larch</td>
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<tr>
<td>western white pine</td>
<td><em>Pinus monticola</em></td>
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<tr>
<td>white spruce</td>
<td><em>Picea glauca</em></td>
</tr>
<tr>
<td>white fir</td>
<td><em>Abies concolor</em></td>
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<tr>
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<td><em>Centaura sosititis</em></td>
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## Common/Scientific Names: Insect and Pathogen Species

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<td><em>Armillaria spp.</em></td>
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<td><em>Adelges piceae</em></td>
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<td><em>Pseudohylesinus variegatus</em></td>
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<td>beech scale</td>
<td><em>Cryptococcus fagisuga</em></td>
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<td>beech scale nectria</td>
<td><em>Nectria coccinea var. faginata</em></td>
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<td><em>Sphenoptera chalcicroa arenosa (Coleoptera: Buprestidae)</em></td>
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<td>coniferous bark beetles</td>
<td><em>Coleoptera: Scolytidae</em></td>
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<td>cypress aphid</td>
<td><em>Cinara cupressa</em></td>
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<tr>
<td>Cytospora canker</td>
<td><em>Valsa kunzei</em></td>
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<tr>
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<td><em>Dendroctonus pseudotsugae</em></td>
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<td>Douglas-fir tussock moth</td>
<td><em>Orgyia pseudotsugata</em></td>
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<td><em>Arceuthobium spp.</em></td>
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<td>Scientific/Common Names: Plant Species</td>
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<td><em>Acer saccharum</em></td>
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<td>Fraser fir</td>
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<td>sugar maple</td>
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## Scientific/Common Names: Insects and Pathogens

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