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Remote Sensing Techniques for Rapid Assessment of Forest Damage Caused by Catastrophic Climatic Events

Remote Sensing Techniques for Rapid Assessment of Forest Damage Caused by Catastrophic Climatic Events

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LIST OF ACRONYMS

AGL	Above ground level
CIR	Color infrared
FHM	Forest Health Monitoring
FIA	Forest Inventory and Analysis
GIS	Geographic information system
GPS	Global Positioning System
PPS	Probability proportional to size
S-VHS	Super video home system
USDA	United States Department of Agriculture
USGS	United States Geological Survey

1. INTRODUCTION

Catastrophic climatic events such as hurricanes, tornadoes, and ice storms can cause billions of dollars in damage to infrastructure and personal property, loss of lives, and damage to natural resources. Forests are especially susceptible to these events. The following is a list of recent climatic events in North America that have had devastating effects on forest resources.

1938—A major hurricane struck portions of southern New England. Forests of eastern white pine (*Pinus strobus*) suffered particularly severe damage.

1962—The "Columbus Day" storm caused severe windthrow in forests on the west slope of the Cascades in portions of Washington and Oregon. Windthrown Douglas-fir provided a large volume of host material suitable for buildup of an outbreak of Douglas-fir beetle (*Dendroctonus pseudotsugae*).

1969—Hurricane Camille, with winds in excess of 200 mi/h, devastated coastal Mississippi, damaged over 1.9 million acres of forests, and created conditions favorable for subsequent outbreaks of pine engraver beetles (*Ips* spp.).

1988—Hurricane Gilbert struck Mexico's Yucatan Peninsula and caused extensive damage to the region's tropical forests and increased fuel levels significantly. During the following year, several large wildfires burned over 310,000 acres in an ecosystem where wildfire is a relatively rare event.

1989—Hurricane Hugo struck the South Carolina coast with sustained winds of 135 mi/h, causing extensive damage to forests in 23 counties. The Francis Marion National Forest, on the South Carolina coast, suffered heavy losses.

1997—Winds in excess of 120 mi/h, associated with an early winter snow, blew east over the Continental Divide in northern Colorado in late October, causing damage in spruce and fir forests on about 20,000 acres of the Routt National Forest. The large volume of downed trees posed an increased hazard of wildfire and provided breeding sites for spruce bark beetle (*Dendroctonus rufipennis*).

1998—A devastating ice storm struck portions of eastern Canada and the northeastern United States in January. Over 17 million acres of forest suffered damage in northern New York and portions of Vermont, New Hampshire, and Maine. A special Federal emergency appropriation was made available to aid in forest recovery (USDA Forest Service 1998).

1999—Winds in excess of 90 mi/h, associated with a severe thunderstorm, resulted in extensive breakage and windthrow of pine, aspen, birch, and other species over 300,000 acres in the Superior National Forest and adjoining state and private lands in northern Minnesota in July. Much of the damage occurred in the Boundary Waters Canoe Area Wilderness, a popular wilderness area known worldwide for canoeing and other forms of outdoor recreation.

Such events often require marshaling of experts from state, private, and Federal sectors to plan, coordinate, and implement recovery efforts. Urban forests, nonindustrial woodlands, industrial forests, and forests managed by state and Federal agencies may be affected. There is an immediate need for information on the location and intensity of the damage relative to key resource values and management objectives such as wildlife habitat, timber resources, urban forests, and recreation. Since these events are relatively infrequent in any one region, there is typically a lack of corporate memory and experience on the part of those who design

and conduct the surveys to obtain the needed information. Moreover, if several states and Federal land areas are affected, individual agencies may independently design surveys that produce data difficult to aggregate on a regional level.

Remote sensing—the collection and interpretation of data using aerial observation, aerial photos, airborne video, or satellite images—is a valuable tool for assessment of damage caused by catastrophic climatic events. Damage to forests caused by hurricanes, ice storms, and other climatic events are often visibly spectacular. This allows for rapid collection of the needed information using remote sensing and at a cost much lower than ground surveys. Moreover, as anyone who has tried to walk through a forest that has just fallen victim to a severe storm can readily attest, damage caused by these events restricts access, making it much more difficult to conduct ground-based inventories. This makes a remote sensing approach especially attractive for these assessments.

The purpose of this manual is to provide forest health specialists, especially those with previous remote sensing experience, a set of guidelines and procedures for planning and coordinating damage assessments, and procedures for using aerial sketchmapping, aerial photos, and airborne video with or without supplemental ground surveys for data acquisition. Some of the procedures described in this manual have been in use for many years while others are the result of recent development and testing. Emphasis is placed on situations where damage has occurred over extensive areas (in excess of 250,000 acres), where sampling rather than complete coverage should be considered, and where the information is needed in a short time to implement salvage and recovery efforts. The methodologies described apply primarily to forest conditions to eastern North America, but can be adapted to other regions.

2. CLIMATIC EVENTS AND FOREST DAMAGE

2.1. CLIMATIC EVENTS THAT CAN CAUSE FOREST DAMAGE

Wind is undoubtedly the most frequent climatic cause of severe forest damage. Cyclonic winds such as those associated with hurricanes, typhoons, tropical storms, and, on a more localized basis, tornadoes cause a twisting action resulting in tree breakage. Resulting windthrow can occur in many directions. Cyclonic winds have damaged forests in many parts of the world, and in some areas, such as the Caribbean Basin, hurricanes and tropical storms are considered to be a major factor in the dynamics of forest ecosystems (Everham 1995). Straight-line winds, associated with low-pressure cells, have been implicated in a number of recent aviation accidents and are also capable of damaging forests. Windthrow cause by these events is generally deposited in a single direction.

Ice and wet snow deposited on tree branches and stems can cause crown damage, bending, and breakage. Snow damage can be especially severe during fall, when deciduous broadleaf trees still have foliage, providing additional surface area on which the snow is deposited. For example, in September 1995, an early snow along the Colorado Front Range caused extensive damage to street, shade, and ornamental trees in Fort Collins and other communities. Large hailstones can shred foliage, defoliate trees, and break and wound limbs and branches.

2.2. FOREST DAMAGE CAUSED BY CLIMATIC EVENTS

Forest damage due to catastrophic climatic events is generally obvious and visible from long distances and consists of various kinds of mechanical injury to tree crowns and/or stems and foliage. The most common damage types are as follows:

1. Snapped or twisted mainstems (Figures 2.1 and 2.2)
2. Uprooting of trees (Figure 2.3)
3. Bending of main stems (Figures 2.4 and 2.5)
4. Broken branches in tree crowns
5. Foliar injury (Figure 2.6)

The type of damage will vary according to the nature and intensity of the climatic event (Table 2.1) and the species and size of trees involved (Everham 1995, Touliatos and Roth 1971).

The most common kinds of damage associated with high winds caused by hurricanes or other large storms is crown and stem breakage (Figures 2.1 and 2.2), uprooting (Figure 2.3), and bending or breakage of the stems of younger trees (Figures 2.4 and 2.5), with trees generally falling in a single direction in a given stand. Tornadoes, on the other hand, are more localized and may lay trees down in several directions within a fairly narrow path. High winds associated with hurricanes and tornadoes, which usually occur at a time of year when broadleaf trees are foliated, may also cause temporary defoliation of broadleaf trees and forests. As a result, mechanical injury such as windthrow is more visible via remote sensing, at least until the surviving broadleaf trees refoliate. Foliage remaining on windthrown trees will fade to a red or red-brown color after several weeks, making damage more visible from the air.

Hailstorms can affect both conifers and broadleaf trees, causing foliage tearing and necrosis (Figure 2.6), and wounding or breaking of branches.

Another type of damage caused by severe winds near coastal areas is foliar injury from salt spray, and tree dieback and mortality due to flooding by brackish water (Touliatos and Roth 1971).

Table 2.1. Types of damage to trees and forests associated with climatic events

Part of tree affected and damage type	Type of climatic event		
	Ice or heavy snow	Hail	Wind
Crown:			
Branch and limb breakage	X	X	X
Defoliation		X	X
Shredding, tearing, and necrosis of foliage		X	X
Stem:			
Bending and leaning	X		X
Breaking	X		X
Uprooting			X

Figure 2.1. Stem breakage in longleaf pine in southern Mississippi caused by Hurricane Camille, 1969

Figure 2.2. Mainstem breakage and windthrow caused by straight-line winds, Superior National Forest, Minnesota, July 1999

Figure 2.3. Uprooting of lodgepole pine (*Pinus contorta*), Engelmann spruce (*Picea engelmannii*), and other conifers caused by high winds, Routt National Forest, Colorado, October 1997

Figure 2.4. Bending of young pines in southern Mississippi following Hurricane Camille, 1969

Figure 2.5. Bending and crown breakage in birch and other broadleaf trees caused by the ice storm of January 1998, northeastern United States

Figure 2.6. Tearing and associated leaf necrosis on Norway maple (*Acer platanoides*) caused by hail, Fort Collins, Colorado, August 1999

Certain tree species and vegetation types are more susceptible to damage than others. A tree's ability to withstand high winds depends on the interaction of five factors: (1) strength of the wood, (2) shape and size of crown, (3) extent and depth of root system, (4) antecedent moisture conditions, and (5) shape of the bole (Touliatos and Roth 1971). Many conifers are shallow-rooted and especially susceptible to uprooting during high winds. During the northeastern ice storm of 1998, paper and yellow birches (*Betula papyrifera* and *B. allegheniensis*) and aspens (*Populus grandidentata* and *P. tremuloides*) were especially susceptible to bending and breakage while eastern white pine (*Pinus strobus*) and northern red oak (*Quercus rubra*) suffered relatively minor injury, consisting primarily of branch breakage. During the severe windstorm that occurred on the Superior National Forest, Minnesota, in July 1999, quaking aspen (*P. tremuloides*), paper birch (*B. papyrifera*), and jack, white, and red pines (*Pinus banksiana, P. strobus,* and *P. resinosa*) were most susceptible to breakage and windthrow, whereas spruce (*Picea glauca* and *P. mariana*), larch (*Larix laricina*), and balsam fir (*Abies balsamea*) suffered less damage.

2.3. SPATIAL DISTRIBUTION OF DAMAGE

Factors that affect spatial distribution of forest damage caused by catastrophic climatic events include height of the forest canopy, site exposure (Foster and Boose 1992), and elevation. Generally speaking, the taller the trees, the greater their susceptibility to severe winds. Exposure is determined by slope orientation and angle. Forest vegetation on a slope directly facing the storm path will receive significantly more damage than the vegetation on the leeward side. Elevation can be a factor in the spatial distribution of damage caused by ice or heavy snow events, which tend to be more severe with increasing elevation.

2.4. DURABILITY OF DAMAGE SIGNATURES

Most types of forest damage caused by catastrophic climatic events are not only highly visible, but the damage will remain visible for a considerable period of time after the event has occurred. Visibility of damage during the summer leaf-on period may become somewhat obscured when broadleaf trees refoliate, which may occur as early as 10–14 days following the event. Experience has shown that ice storm damage incurred during winter can still be resolved and classified on leaf-on color infrared (CIR) aerial photos taken at a scale of 1:8,000 during the summer leaf-on period following the event. However, damage may be much less visible two growing seasons following the event because surviving trees with crown damage begin to put out adventitious growth.

3. PLANNING FOREST DAMAGE ASSESSMENTS

Planning, the obvious critical first step, is especially important if the damage is widespread and if several states or a number of teams are involved in the data collection. In the case of a catastrophic event where there is extensive private property and infrastructure damage, injuries, and possible loss of human lives, forest resources will obviously take a lower priority. Air space over the most severely affected areas may be closed to aircraft other than those engaged in search and rescue operations. Therefore, while there may be a perceived urgency to gather information on forest resource damage, there is also time available to plan and coordinate the assessments.

Key items to consider when planning special surveys for assessment of forest damage caused by climatic events are as follows:

1. Data requirements
2. Classification standards
3. Stratification
4. Tools available

Before an effective forest damage assessment can be designed, there must be a common understanding of the information needs and the time frame within which the information is needed.

3.1. WHY, WHAT, AND WHEN?

3.1.1. Questions That Must Be Addressed

Information on forest damage caused by catastrophic climatic events is needed to address a number of questions including the following:

1. Is there a need for disaster declaration or request for emergency Federal funding?

2. Is there a need for specific immediate and long-term actions, such as:

   A. Opening of key roads, trails, and other access?
   B. Salvage and utilization of damaged timber?
   C. Rehabilitation of damaged forests?

3. Is there a need for local and regional responses to changes in:

   A. Wood supply?
   B. Special forest products (e.g., maple syrup)?
   C. Recreational activities?

4. Did the event set the stage for possible secondary effects, such as:

   A. Buildup of insect pests in damaged trees that may subsequently attack stressed but still standing trees?
   B. Increased wildfire hazard due to fuel loading?

3.1.2. Data Elements

The information required to provide at least the initial answers to these questions are relatively straightforward and include the following:

1. Location of Damage—There will be a need to map the location of damaged areas with respect to:

   A. State, county, and other major political or administrative subdivisions such as national forests, state forests, national parks, Tribal lands, and industrial forest lands
   B. Physiographic or biological subregions of the landscape such as mountain ranges, river basins, elevation zones, or vegetation types (e.g., broadleaf forests vs. conifer forests)
   C. Land management objectives such as wilderness and other special designations vs. general forest areas where timber salvage is usually a viable option

2. Intensity of Damage—Information may be needed on the area and location of damage by different intensities.

Most data requirements will be satisfied by a series of map products and statistical tables summarizing area damaged by intensity classes, political or administrative subdivisions, physiographic or vegetation types, and land management objectives.

Occasionally, there may be a need to satisfy one or more unique data requirements. For example, when a severe storm on 4 July 1999 struck portions of the Boundary Waters Canoe Area Wilderness of the Superior National Forest in northern Minnesota, an area well known for its outstanding canoeing, a critical and immediate data requirement was to identify portage routes blocked by windthrown trees so that access to lakes could be reopened in the shortest possible time. Similarly, after the ice storm of January 1998, one of the key issues to be addressed was the extent of damage in sugar maple (*Acer saccharum*) and potential impacts on the maple sugar industry (NEFA 1998). The need to address these requirements must be identified through discussions with appropriate forest officers (e.g., state foresters, national forest supervisors, district rangers, industrial foresters) during planning.

3.1.3. Timing

There will very likely be an urgent time frame (10 days to 1 month) within which at least some of the data must be available to support key management decisions. Consequently the time frame within which the data are required will be a major factor in selecting the appropriate survey methodology.

During planning, it will be necessary to determine the following:

1. Information needed during the first few days following the event
2. Information needed within the first month following the event
3. Information needed between 6 and 12 months following the event

An example of timing requirements for information needed to support actions outlined in Section 3.1 is given in Table 3.1.

Table 3.1. Example of timing requirements for data required to support actions in response to forest damage caused by climatic events (note: these may vary according to local conditions)

Action required	Time after event		
	Within 1–7 days	Within 1 month	Within 6–12 months
Determine need for disaster declaration	X		
Open roads, trails, and other access	X		
Salvage and utilization of damaged timber		X	
Rehabilitation of damaged forests			X
Respond to changes in wood supply and other resources[a]			X
Respond to possible secondary effects (insects, disease, fire)[b]		X	X

[a] Data to support this need are generally provided by Forest Inventory and Analysis units (e.g., Sheffield and Thompson 1992).
[b] These assessments are primarily done via ground surveys.

3.2. CLASSIFICATION STANDARDS

Prior to any survey, it is important to define the damage strata used to classify affected areas so that all aerial observers or image analysts have a common understanding of how damage is to be mapped.

Classification standards should be based on a combination of data requirements and what can be realistically seen and classified. Generally, the simpler the classification system, the more consistency will be achieved. In some instances, where damage is localized and fairly uniform, a binary division into “no visible damage” and “aerially visible damage” may be all that is needed. Other classification schemes, which stratify damage into three or more intensity classes**,** have also been used to map forest damage (Table 3.2).

Table 3.2. Examples of standards used to classify damage caused by climatic events

Classification system		
Binary (two-class)	**Three-class**	**Four-class**
Undamaged **Damaged**: Occurrence of windthrown, bent, or broken trees without regard to intensity. The breaking point between the two classes might be defined by some agreed upon damage level (e.g., < 10% and ≥ 10% damage).	**Undamaged** **Light to moderate**: Windthrown, bent, or broken trees visible but do not exceed 50% of the dominant/ codominant trees in the stand **Heavy or severe**: > 50% of the dominant/codominant trees in the stand windthrown, bent, or broken	**Undamaged** **Light**: 10–33% of trees windthrown, bent, or broken **Moderate**: 34–67% of trees windthrown, bent, or broken **Heavy**: ≥ 68% of trees windthrown, bent, or broken

Recently national standards for aerial sketchmapping have been developed by the U.S. Department of Agriculture (USDA) Forest Service for most types of pest damage visible from the air and damage caused by climatic events (USDA Forest Service 1999).

To ensure that all aerial observers and image interpreters understand the system and use it consistently, 35 mm aerial oblique photos or digital images may be taken of various damage intensities. If a standard film camera is used, photos should be taken with a natural color transparency or negative film with an ASA of 100 or 200.[1] A fast shutter speed (1/250 to 1/1000 of a second) should be used to minimize image motion. These photos can be used to help define the classification standards and to train teams of aerial observers or image interpreters.

3.3. STRATIFICATION

Stratification is the division of a population into subunits (strata) with a common set of attributes in order to provide more precise population estimates or to have separate estimates for several subpopulations (Freese 1967).

3.3.1. Damage Classes

Stratification by intensity of damage will provide data on the spatial distribution of various degrees of damage across the landscape. This should provide clues as to the distribution of damage relative to the path of the climatic event, topography, slope, aspect, and elevation, especially if these data themes are already stored in a geographic information system (GIS). Damage class stratification will also allow for selection of second stage samples or visitation of existing inventory plots according to damage intensity, thus increasing the precision of subsequent population estimates.

3.3.2. Vegetation Types

Most forests are a mosaic of vegetation types defined by factors such as soils, available moisture, aspect, and elevation. It is important to know which forest types were more severely affected by the event and which types suffered relatively little damage. This is especially true if there are significant differences in the ecological, economic, and social benefits afforded by the various vegetation types in the affected area.

3.3.3. Political or Administrative Units

Data on the distribution and intensity of forest damage will undoubtedly be needed at the state level and may, in some cases, be needed at the county level. It may also be necessary to provide data by land use or ownership classes and administrative units (e.g., Federal, state, industrial private, and nonindustrial private).

Forest resource information collected by the USDA Forest Service's Forest Inventory and Analysis Program is provided at the state and county level. Another tier of information available from Forest Inventory and Analysis is survey or geographic unit. These are groups of counties with more or less similar vegetation, physiography, or land use (Figure 3.1). Survey or geographic units may be a desirable way to subdivide a large area and to summarize data on damage caused by a climatic event. This can permit a direct interface to existing forest resource information.

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[1] Kodachrome 64 or 200 films are *not* recommended for this purpose because they require special processing and may not be available for several days. Color transparency films that use the Kodak E-6 processing chemistry such as Kodak Elite Chrome can be processed locally and are usually available for use within 24 hours.

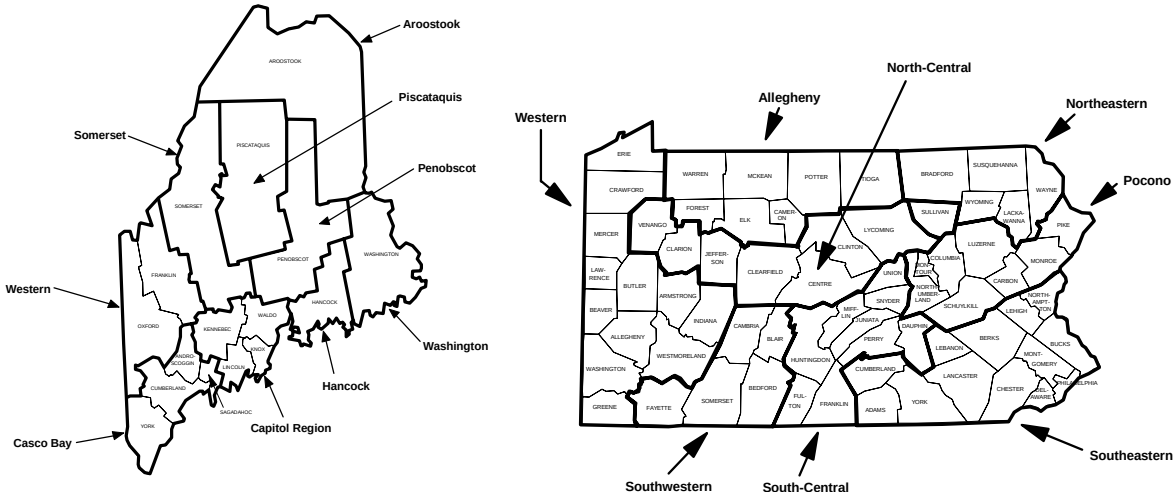

Figure 3.1. Geographic units in Maine and Pennsylvania. Large counties in eastern Maine are treated as individual geographic units.

3.4. REMOTE SENSING AND SUPPORTING TECHNOLOGIES AVAILABLE

Several remote sensing tools are available for rapid assessment of forest damage caused by catastrophic climatic events. These include aerial sketchmapping, aerial photography, and airborne video imagery. Each has distinct advantages and disadvantages that must be evaluated against the data requirements and the time frame within which the data must be available. Several other remote sensing tools such as small format digital camera systems and earth orbiting satellite imagery have potential use for rapid assessment of forest damage caused by climatic events, but operational techniques for their use have not yet been developed.

Related tools available to support acquisition of data on forest damage caused by climatic events by remote sensing include the U.S. Global Positioning System (GPS) and GIS.

GPS is a satellite-based positioning system operated by the Department of Defense and was initially designed to provide an accurate, 24-hour, worldwide, all weather positioning system for military aircraft. This system consists of 24 earth-orbiting satellites, each of which continuously transmits time and navigational signals. A network of control and monitor stations calculate and transmit satellite positions and clock corrections to the satellites. GPS receivers capture data transmitted by satellites and compute the latitude and longitude of the receiving station. Although originally designed for military use, GPS has found a wide range of civilian applications including the natural resource sciences.

GIS are data storage and manipulation systems that make it possible to make maximum use of the spatial information obtained by remote sensing. These systems facilitate storage, manipulation, integration, analysis, and display of spatial data derived from remote sensing and other sources. GIS consists of computer hardware and software as well as the personnel and operating data to go into the system.

4. AERIAL SKETCHMAPPING

Aerial sketchmapping is the oldest and most widely used remote sensing tool for mapping forest damage caused by forest insects and disease (Ciesla 2000). It has also been widely used for mapping damage caused by climatic events. It is a simple, low-cost method of damage mapping during which trained aerial observers, in small aircraft, locate damaged areas and sketch their locations onto maps as coded points or polygons according to predetermined classification standards.

General 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) and for the entire United States (Klein and others 1983). More recently, national standards have been developed by the USDA Forest Service for sketchmapper training, mapping thresholds, certification standards, severity ratings, coding standards, and coordination (USDA Forest Service 1999)

Aerial sketchmapping is a flexible, cost-effective means of covering large areas of remote, inaccessible forests rapidly. An experienced survey team can cover up to 750,000 acres in a day. Resource professionals working as aerial observers can develop firsthand knowledge of conditions over a wide area, and a map product is available immediately. Unfortunately, data obtained from aerial sketchmapping are subjective, not necessarily repeatable, and there is no permanent record of damage other than the map products produced by the aerial observers. Aerial observers must know their exact location at all times and even a moment's confusion can result in plotting an area of damage in the wrong location. The quality of aerial sketchmap data, therefore, depends on the skill and experience of the aerial observers and their familiarity with local forest conditions and damage signatures. Weather conditions affecting visibility and air turbulence also influence the quality of aerial sketchmap data.

Forest damage caused by climatic events is highly visible from low flying aircraft (Figures 4.1, 4.2, and 4.3), and sketchmapping has been widely used for many years for mapping the location of areas affected by these events (e.g., Anon. 1999, Terry and others 1969).

4.1. OPERATING PARAMETERS

Aerial sketchmapping is routinely used throughout North America for mapping of forest damage caused by a variety of forests insects and diseases, especially tree killing bark beetles and defoliators. The operating parameters are well documented (Klein and others 1983) and known by forest health protection specialists; therefore, they will be just briefly summarized in the following sections.

4.1.1. Aircraft

High-wing single engine, fixed-wing aircraft such as the Cessna 172, 182, 206, or 210 are most widely used for sketchmapping. These aircraft combine high ground visibility, maneuverability, ability to fly at slow speeds, and relatively low operating costs. Some high-wing twin-engine aircraft have also been used with varying success. Multiengine aircraft provide an extra measure of safety but are more expensive to operate and may not have the ground visibility or slow flying capabilities of single-engine aircraft. Twin-engine aircraft that have been used for aerial sketchmapping include the Cessna 337 Skymaster, the Aero Commander 500 series, and the Partenavia P 68 series.

Figure 4.1. An aerial sketchmapper's view of windthrow caused by Hurricane Camille in Mississippi during 1969 (note faded foliage on the windthrown pines, increasing the visibility of the damage)

Figure 4.2. Aerial view of foliage injury to a ponderosa pine forest in Colorado caused by a severe hailstorm (photo by Dennis Will and courtesy of Dave Leatherman, Colorado State Forest Service)

Figure 4.3. Damage to birch and aspen caused by straight-line winds, Superior National Forest, Minnesota (photo from *www.gis.umn.edu/snf/storms/html*)

Small helicopters are also excellent aerial sketchmap aircraft because they can fly at slower speeds and at lower altitudes, and are more maneuverable than fixed-wing aircraft. However, they are considerably more expensive to operate.

4.1.2. Airspeed and Flying Height

Airspeeds in the range of 90–125 mi/h are ideal for sketchmapping. Above ground level (AGL) flying height should average between 1,000 and 2,500 feet.

4.1.3. Maps

Maps at scales ranging between 1:50,000 and 1:125,000 are adequate for general-purpose sketchmapping. Topographic maps are preferred over planimetric maps, if available. Examples of map bases that have been widely used for aerial sketchmap surveys include USDA Forest Service or Bureau of Land Management (BLM) planimetric maps at a scale of 1:126,720 (1/2 inch = 1 mile) and the U.S. Geological Survey (USGS) 1:100,000 scale metric topographic maps. The 7.5-minute, 1:24,000 scale USGS topographic maps or orthophotos are excellent for intensive mapping of small, localized areas but are too large a scale for mapping large areas because many maps are required. Some aerial observers find it awkward to have to change maps every few minutes in the confined space of a small aircraft.

4.1.4. Aerial Observer Skills

Aerial observers should be familiar with forest vegetation and have a working knowledge of forest damage signatures. They should not be subject to motion sickness, have good eyesight and normal color perception, and have the ability to read maps and orient between the air and the ground. Experience has shown that about 100 hours of in-flight experience are required before aerial observers become proficient sketchmappers.

4.1.5. Flight Patterns

There are two basic types of flight patterns: contour and grid. Contour flying is done in mountainous terrain and the flight path follows the general terrain. A typical contour flight pattern consists of flying parallel to individual drainage basins. Grid flying is done in areas of level, poorly defined terrain. The aircraft is flown in a series of straight flight lines at specified distances of 1 to 6 miles.

4.1.6. Data Products

The primary products of sketchmap surveys are maps showing the location of damaged areas and reports or tables of statistical summaries of damage by intensity class (Figures 4.4 and 4.5, Table 4.1). Today GIS is the standard tool for map production, data analysis, storage and retrieval, and development of historical databases on forest damage and is a natural repository for spatial data on forest damage from catastrophic climatic events (Figure 4.6).

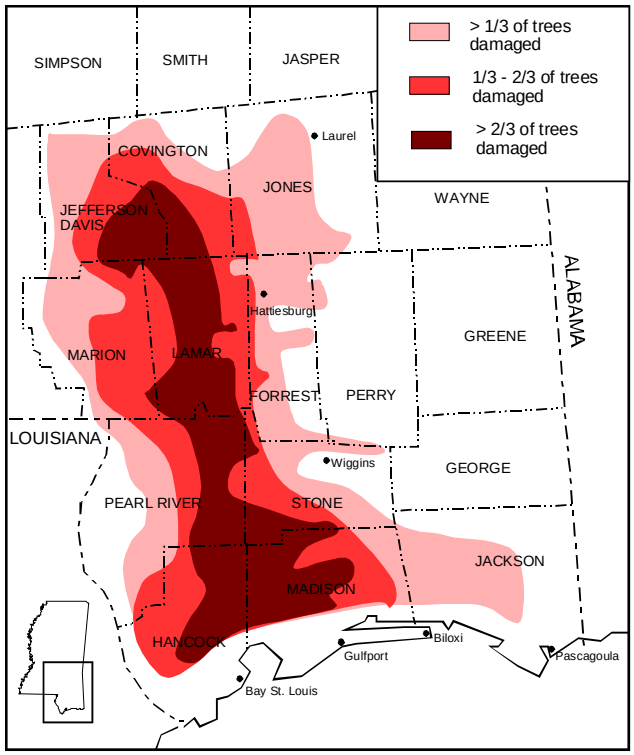

Figure 4.4. Map of forest damage caused by Hurricane Camille in southern Mississippi in 1969 (adapted from Terry and others 1969)

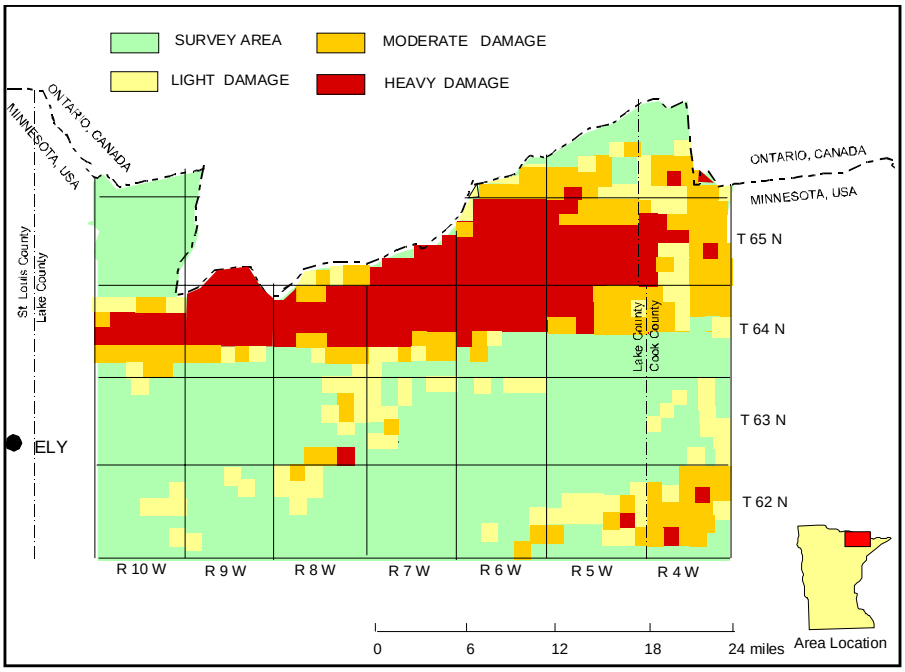

Figure 4.5. Map of a portion of the area damaged by severe winds on 4 July 1999, Superior National Forest, Minnesota, based on classification of damage in 1-square-mile sections (adapted from Anon. 1999)

Table 4.1. Acres of commercial forest damaged by Hurricane Camille, Mississippi, 1969

County	Light[a]	Moderate[b]	Heavy[c]	Total
Covington	65,434	52,710	12,723	130,867
Forest	127,072	15,249	0	142,321
Hancock	0	39,270	91,303	130,573
Harrison	53,175	53,175	76,483	182,833
Jackson	109,465	0	0	109,465
Jefferson Davis	81,114	13,030	27,483	121,182
Jones	146,170	17,795	0	163,965
Lamar	20,698	82,790	127,008	230,496
Marion	111,264	84,326	1,952	197,542
Pearl River	110,216	36,883	82,445	229,544
Perry	25,163	0	0	25,163
Stone	95,519	77,066	17,910	190,495
Total	945,290	472,294	436,862	1,854,446

[a] Light: < $^1/_3$ of trees damaged
[b] Moderate: > $^1/_3$ but < $^2/_3$ of trees damaged
[c] Heavy: > $^2/_3$ of trees damaged
(Source: Terry and others 1969)

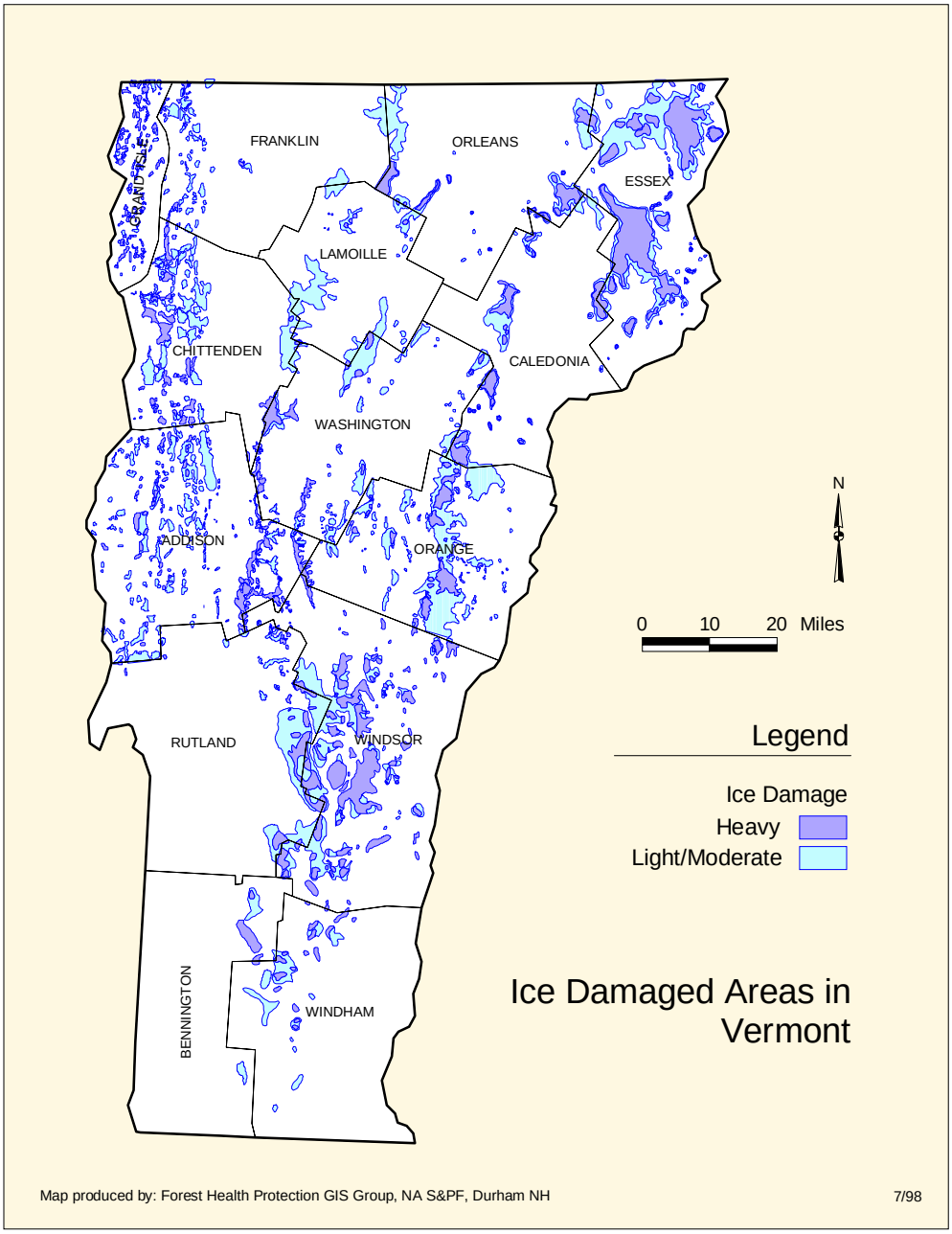

Figure 4.6. Map of 1998 ice storm damage in Vermont produced from sketchmap data by GIS (NEFA 1998)

4.2. APPLICATIONS

Aerial sketchmapping is the preferred tool for rapid assessments of forest damage caused by climatic events. Applications include general reconnaissance, stratification, and damage mapping.

4.2.1. Reconnaissance

Aerial reconnaissance surveys are informal flights made immediately after the event has occurred to outline the affected area and develop classification standards for later use. The damage outline shows, in the broadest terms, the general area affected by the event. Information can be obtained on counties affected and the general distribution of damage relative to various forest types, elevation, and topographic features.

Reconnaissance surveys can help develop the classification standards for more detailed mapping by sketchmapping, photography, or airborne video. Aerial reconnaissance surveys give experienced aerial observers an opportunity to study the various damage signatures and develop logical damage classes. Color photos of representative damage types will be of value when developing formal classification standards and training aerial survey teams or image analysts.

4.2.2. Stratification

A second application for sketchmapping is to stratify areas of forest into broad classes for subsequent sampling in a multistage or multiphase sampling configuration. Sketchmapping is used to delineate large polygons of more or less similar damage intensity. These polygons can then be sampled either with aerial photos, airborne video, or via existing networks of permanent ground plots (e.g., forest inventory plots, forest health monitoring plots) if more detailed estimates of areas damaged by various damage strata with specified levels of confidence are needed (see Chapter 5, Section 5.3).

4.2.3. Damage Mapping

Aerial sketchmapping has been widely used for mapping specific locations of damage caused by catastrophic climatic events. For example when Hurricane Camille struck coastal Mississippi on 17 August 1969, sketchmap surveys were conducted over 14 counties and a gross area of 3.8 million acres. The survey was conducted using a Cessna 182 aircraft from an altitude of 1,000 feet AGL on a series of east-west flight lines at 4-mile intervals. Two experienced aerial observers mapped damage on a 1-mile-wide strip either side of the flight line for a 50 percent sample according to three damage classes.

The survey was completed within 1 week of the storm event, and data were made available to the Mississippi Forestry Commission the following month (Terry and others 1969, Table 4.1, Figure 4.4). When a severe storm struck the Boundary Waters Canoe Area Wilderness of the Superior National Forest in northern Minnesota on 4 July 1999, a sketchmap survey was conducted and resultant data were entered into a GIS at the University of Minnesota. A damage map was available on the Internet by 23 July 1999 (Anon. 1999).

In order for damage mapping by sketchmapping to be effective, it is essential that experienced aerial observers be used for the data collection and that a clear set of classification standards be developed and adhered to by all aerial survey teams involved in the assessment.

5. AERIAL PHOTOS

Of all of the remote sensing tools presently available, aerial photos produce images of the highest spatial resolution. When taken with the appropriate combination of lens, film, and flying height, it is possible to resolve individual tree crowns and detect subtle symptoms of pest or disease occurrence. Most forest damage caused by climatic events is easily resolved on aerially photos (Figure 5.1).

Figure 5.1. Color infrared aerial photo taken at a scale of ca. 1:16,000 depicting forest damage caused by a tornado in central Pennsylvania (note the cyclonic pattern of windthrow in the affected areas)

In contrast to aerial sketchmapping (discussed in the previous chapter), aerial photos provide a record of conditions at a given point in time that can be reexamined should questions arise as to possible errors in the location and severity of damage. The cost of aerial photos, on the other hand, is considerably more expensive than aerial sketchmapping. Aerial films also require special processing and must be shipped to companies that provide this service, causing a delay before the film is available for interpretation. Moreover, aerial photos must be indexed before they can be interpreted, another time-consuming task. Another drawback of aerial photo acquisition is that in some areas the incidence of cloud cover severely limits the number of days during which aerial photos can be acquired.

5.1. SOME BASICS ABOUT AERIAL PHOTOS

Aerial photos can be acquired in a wide range of formats, scales, and films; some of the basics are covered in the following sections. More detailed information can be obtained from references such as Ciesla (2000) and Lund (1997).

5.1.1. Formats

The most widely used aerial photo film format is 9 by 9 inches (230 by 230 mm). Other commonly used formats include 35 mm and 70 mm, commonly referred to as “small-format” photos, and “large formats” such as taken with a 9- by 18-inch camera or a panoramic aerial camera. The latter are generally taken from aircraft capable of flying at high altitudes (30,000 to 65,000 feet) such as the ER-2 reconnaissance aircraft operated by NASA.

Nine-inch aerial photos are the most popular because at contact scale each photo covers a relatively large area of land (Table 5.1). This is especially important when using aerial photos for sampling because it is relatively easy to locate ground points on both the photos and on corresponding maps to pinpoint photo location. Acquisition of 9-inch aerial photos usually requires contracting with a company that specializes in providing this service, although some USDA Forest Service units and state forestry agencies have aircraft equipped for handling 9-inch camera systems. Small format cameras, on the other hand, are more readily available and can be easily installed in a small aircraft equipped with a camera hatch. Small-format systems cover considerably less land area at any given contact photo scale, thus making it more difficult to locate the area covered by the photo on the ground. Large format systems have been used successfully for a number of forest health applications (e.g., mapping of widespread defoliation by gypsy moth); however, it is difficult to schedule aircraft capable of flying high altitude missions on the short notice typically required of surveys of catastrophic climatic events.

Table 5.1. Comparison of land area covered by 35-mm, 70-mm, and 9-inch aerial photos at photo scales most commonly used in forest health applications of remote sensing

Photo scale	Land area covered (acres)		
	35-mm	70-mm	9-inch (230-mm)
1:2,000	0.85	3.97	51.65
1:4,000	3.39	15.89	206.61
1:6,000	7.62	35.76	464.88
1:8,000	13.55	63.57	826.45
1:12,000	30.48	143.02	1,859.50

5.1.2. Films

A variety of aerial films are available, including black and white (panchromatic), natural color, and color infrared (CIR). In addition, some aerial films are designed for processing to a negative from which paper positive prints are made; other films are designed for processing to a positive transparency, or diapositive, for viewing on a light table.

Because most forest damage caused by insects and disease involve a change in color of affected tree crowns, natural color and CIR films have been widely used for damage assessment. CIR film is a false color film sensitive to the green, red, and near infrared portions of the electromagnetic spectrum. This film has been used successfully to differentiate certain vegetation types (e.g., conifer vs. broadleaf) and to increase the contrast between certain types of forest damage, such as insect defoliation, and undamaged areas. Moreover, since this film is always used in combination with a medium yellow (minus-blue)

filter, capable of penetrating atmospheric haze, it often yields clearer images than can be produced by natural color films, especially from high altitudes. Disadvantages of CIR film include high contrast and poor shadow penetration, which can make it difficult to resolve downed trees under canopy shadow, and the false color nature of the resultant images, which can confuse inexperienced photo interpreters. More detailed descriptions of the nature and uses of CIR film in forestry and forest health protection are given by Ciesla (2000), Greer and others (1990), and Klein (1982).

Experience has shown that for assessment of forest damage caused by catastrophic climatic events, both color and CIR films can produce acceptable results (Figures 5.2 and 5.3). For conditions typical of eastern North America, where forests are often a mix of broadleaf and conifer stands and where atmospheric haze can be a problem, especially during summer, the following general guideline can be used for film selection:

Winter (leaf off):	Natural color (Kodak SO-359 or equivalent)
Summer (leaf on):	Color infrared (Kodak 2443) with minus-blue filter

Positive transparency (diapositive) films are recommended over negative or print films because transparencies tend to have higher image resolution than paper prints made from negatives.

Figure 5.2. Portion of a 1:9,000 scale color aerial photo taken over a forested area in southern Maine damaged by the ice storm of January 1998

Figure 5.3. Portion of a 1:8,000 scale CIR aerial photo taken over the Bartlett Experimental Forest, White Mountain National Forest, New Hampshire, showing varying levels of damage caused by the ice storm of January 1998

5.1.3. Scales

Scale is the ratio of the distance on a photo or a map to its corresponding distance on the ground. A scale in which one unit on the photo equals 24,000 units on the ground may be expressed as a ratio (1:24,000), a representative fraction (1/24000), or an equivalence (1 inch = 2,000 feet). For forest damage assessments, the most widely used photo scales have been from a range of 1:4,000 to 1:12,000, with 1:8,000 being the most common. Nine-inch aerial photos are generally acquired and used at the same scale. Small format photos are sometimes acquired at small scales and enlarged to a larger scale; however, this requires using prints as opposed to transparencies and results in loss of resolution.

5.2. COMPLETE AERIAL PHOTO COVERAGE

Complete aerial photo coverage is a viable means of assessing forest damage, especially over relatively small areas of land (generally less than a gross area of 250,000 acres). For larger areas, the number of aerial photos required for stereo coverage may be overwhelming (Table 5.2), and photo acquisition costs may be prohibitive if the objective of the photography is simply rapid assessment of damage. Furthermore, availability of suitable weather for photo acquisition over such large areas of land could be a limiting factor. Despite these limitations, aerial photos have been acquired over extensive areas following storm events. For example, after the ice storm of January 1998, the Maine Forest Service acquired complete aerial photo coverage of the most severely damaged areas of the state (ca. 2.8 million acres) at a scale of 1:9,000. These photos addressed two objectives: rapid assessment of forest damage and production of detailed damage maps to help foresters and landowners make site-specific management decisions for forest recovery (USDA Forest Service 1998).

Table 5.2. Number of aerial photos required for 100 percent coverage at 60 percent overlap and 30 percent sidelap of survey units of given size at three photo scales

Area (acres)	Area (square miles)	Photo scale		
		1:4,000	1:8,000	1:16,000
250,000	391	4,692	1,173	547
500,000	781	9,372	2,343	1,093
1,000,000	1,563	18,756	4,689	2,188
2,000,000	3,125	37,500	9,375	4,375
4,000,000	6,250	75,000	18,750	8,750
10,000,000	15,625	187,500	46,875	21,875

If complete aerial photo coverage is required, the photo mission should be planned to provide for a minimum of 60 percent overlap and 20 percent sidelap to allow for stereo viewing. All damaged areas should be mapped according to a predetermined set of classification standards. Polygons of damage may be drawn directly on the aerial photos (prints or transparencies) or on clear plastic sleeves designed to protect aerial photo transparencies. Damage polygons can be transferred to a map base either by sketchmapping or by use of a zoom transfer plotting scope for ultimate entry into a GIS (Figure 5.4).

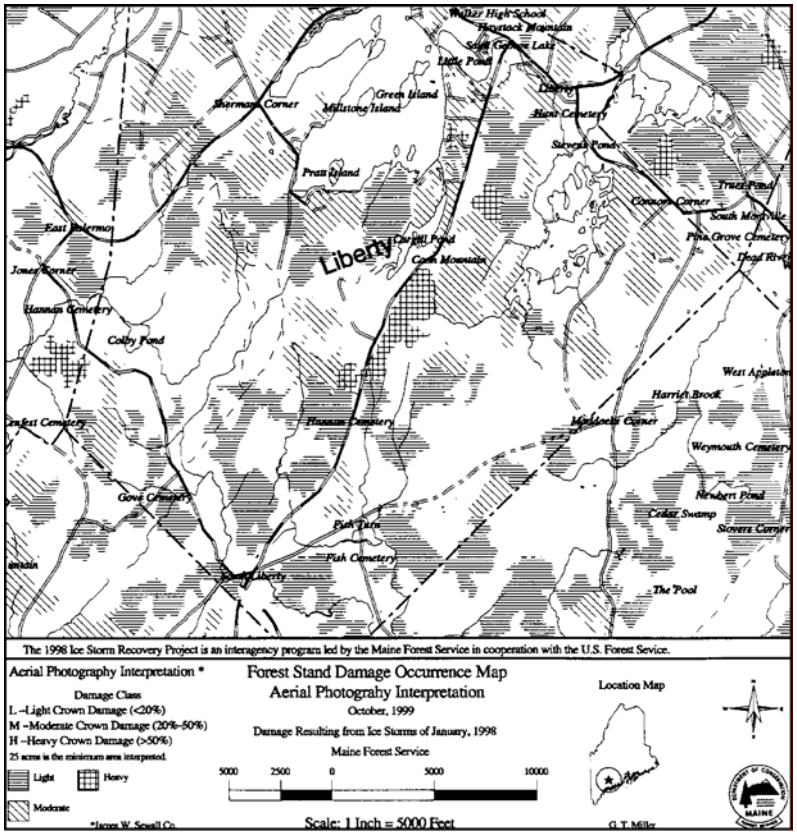

Figure 5.4. Portion of a GIS map of forest damage caused by the ice storm of January 1998 produced from interpretation of aerial photos in Maine

5.3. SAMPLING WITH AERIAL PHOTOS

Sampling is a process in which a portion of a population is used to describe the characteristics of the entire population and is a common practice when using small or standard format aerial photos or airborne video imagery (see Chapter 6) for assessments of forest health or damage. Aerial photo sampling usually consists of from two to five photos taken in a strip with sufficient overlap from one photo to the next to assure stereo coverage, on predetermined intervals along flight lines. Either an entire unit (e.g., national forest, county, or state) or a portion of a unit, within which areas of concentrated damage have been established by a previous survey (e.g., sketchmapping), may be covered. 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 photo mission. This will introduce an element of randomness (quasi-random) into the distribution of photo sample points over the area to be surveyed.

Multistage or multiphase sampling designs have been widely used for assessments of forest damage or forest health involving aerial photos. In multistage sampling, the sampling units are selected in stages, and samples at each stage are taken from sampling units or clusters of units selected in the previous stage. 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. Multistage or multiphase designs that use combinations of sketchmapping, aerial photography, and ground data in forest damage assessments include double sampling with regression (Wear and others 1966) and probability proportional to size (PPS) sampling (White and others 1983).

The following sections describe a procedure for estimating area and severity of damage caused by a climatic event over a large area of forest using aerial photos as a sampling tool. This procedure can be used as a stand-alone survey on a statewide or regional basis, or as a second stage sample following stratification by aerial reconnaissance surveys (see Chapter 4, Section 4.2.2). The design is adapted from an inventory of the health of hardwood forests used in Vermont (Kelley and Eav 1987, Kelley and others 1992, 1997) and consists of classification of blocks of 2.5-acre cells on either color or color infrared (CIR) aerial photos according to vegetation type and intensity of damage. The sample data analysis presented in this section is based on a demonstration conducted over a 250,000-acre test site in Maine affected by the ice storm of January 1998.

5.3.1. Design

1. Sample Blocks—Each sample block consists of a minimum of three 1:8,000 scale, 9-inch photos[1] with at least 60 percent overlap for stereo viewing (stereo triplet). A 250-acre sample block, subdivided into 100 2.5-acre (ca. 1-hectare) units in a 10 by 10 grid should be centered over the principal point of the center photo (Figure 5.5).

[1] In relatively remote areas, where there are few terrain or cultural features that can be used to pinpoint the precise location of the photo sample for ground checking, a strip of more than three photos may be required.

AERIAL PHOTO 2.5-ACRE GRID CELL OVERLAY
FOR VEGETATION TYPE/DAMAGE CLASSIFICATION
Photo scale = 1:8,000

	A	B	C	D	E	F	G	H	I	J
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

Figure 5.5. Pattern for 250-acre sample block overlay subdivided into 2.5-acre samples

2. Number of Photo Samples—A minimum of 30 photo samples should be taken in any given stratum. A general guide for the number of photo samples taken and their spacing, based on the area to be surveyed, is given in Table 5.3.

3. Interval Between Photo Samples—Flight line interval and interval between photo points on a flight line can be determined from the following equation.

   $I = \sqrt{(M/n)}$

   Where:

   I = Flight line and photo point interval in miles
   M = Area of damage class in square miles
   n = Number of photo samples

Table 5.3. General guide for determining the number of 250-acre aerial photo samples to be taken over a given damage class and their appropriate spacing

Area of damage class (acres)	Area of damage class (square miles)	Percent of area to be sampled	Sample area (acres)	Number of 250-acre photo samples	Interval between flight lines and photo points (miles)
250,000	391	3.00	7,500	30	3.61
500,000	781	2.00	10,000	40	4.42
1,000,000	1,563	1.50	15,000	60	5.10
2,000,000	3,125	1.00	20,000	80	6.25
4,000,000	6,250	0.75	30,000	120	7.22
10,000,000	15,625	0.50	50,000	200	8.84

5.3.2. Photo Interpretation

1. Scale Verification—Using an existing map base (e.g., USGS 1:24,000 scale), determine average scale of each photo sample by measuring the distance between several points that can be seen both on the photos and on the map using the following relationship:

$$\frac{\text{photo scale}}{\text{map scale}} = \frac{\text{photo distance}}{\text{map distance}}$$

2. Grid Overlays—Make a series of 10 by 10, 2.5-acre clear plastic overlay grids at equivalent scales (Figure 5.5) ranging from 1:7,000 to 1:9,000 at 250-unit scale intervals (1:7,000; 1:7,250; 1:7,500; 1:7,750; . . . 1:9,000). Individual cell dimensions for each photo scale are given in Table 5.4.

3. Grid Overlay Placement—Select the grid overlay that most closely matches the actual photo scale and center it over the principal point of the center photo of the triplet.

Table 5.4. Two- and 1/2-acre grid cell dimensions at photo scales between 1:7,000 and 1:9,000

Actual scale of aerial photo	Grid cell dimension (inches)
1:7,000	0.566
1:7,250	0.546
1:7,500	0.528
1:7,750	0.511
1:8,000	0.495
1:8,250	0.480
1:8,500	0.466
1:8,750	0.453
1:9,000	0.440

4. Classification of Forest Vegetation—Examine each photo sample block in stereo and classify each 2.5-acre grid cell into one of the following vegetation classes:

   N (Nonforested): More than 50 percent of grid cell occupied by water, pasture, urban areas, open bogs, orchards, cloud cover, etc.

   C (Conifer): More than 50 percent of grid cell forested and occupied by conifers (e.g., pine, spruce, fir, hemlock)

   M (Mixed-wood): More than 50 percent of grid cell forested, 25–49 percent of forested portion of cell occupied by conifers; remaining forest cover consists of broadleaf deciduous species (e.g., maples, birch, oak)

   B (Broadleaf): Forested cells with less than 25 percent the forested area composed of conifers

5. Classification of Damage—Classify each *forested* 2.5-acre grid cell into one of the following three damage classes:

   0 (No visible damage)

   L-M (Light-Moderate): Visible damage present in cell but less than 50 percent of trees bent, windthrown, or with broken crowns

   H (Heavy): More than 50 percent of trees bent, windthrown, or with broken crowns

   On CIR leaf-on aerial photos, classes of storm damage intensity can be recognized as follows (Ciesla and Frament 1999):

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

   Light-Moderate Damage—Occurrence of a scattering of uprooted, 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.

   Record all data on a data sheet such as the one shown in Figure 5.6.

6. Potential Sources of Classification Error—Although damage signatures associated with catastrophic climatic events are easily recognizable, several other signatures appearing on CIR leaf-on aerial photos have been identified as possible sources of photo interpretation error, especially for photo interpreters with limited experience (Ciesla and Frament 1999).

Aerial Photos _____

AERIAL PHOTO 2.5-ACRE GRID CELL
VEGETATION TYPE/DAMAGE CLASSIFICATION

State: *Maine* Subregion: *SW* Project: *98 ice storm*

Photo Plot: *21* Date: *07 July 98* Photo Interpreter: *Dole*

	A	B	C	D	E	F	G	H	I	J
1	*N*	*N*	*C, 0*	*C, 0*	*C, 0*	*M, L-M*	*B, L-M*	*B, L-M*	*B, H*	*B, H*
2	*N*	*C, 0*	*C, 0*	*M, L-M*	*M, L-M*	*B, L-M*	*B, L-M*	*N*	*B, L-M*	*B, H*
3	*N*	*C, 0*	*C, L-M*	*M, L-M*	*M, L-M*	*B, L-M*	*B, L-M*	*B, L-M*	*B, H*	*B, H*
4	*M, 0*	*C, 0*	*C, L-M*	*C, 0*	*M, L-M*	*M, L-M*	*B, 0*	*B, L-M*	*B, L-M*	*B, H*
5	*M, 0*	*C, 0*	*C, 0*	*C, 0*	*M, L-M*	*M, H*	*B, L-M*	*B, L-M*	*B, L-M*	*B, H*
6	*B, 0*	*B, L-M*	*B, L-M*	*B, H*	*B, H*	*B, H*	*B, H*	*N*	*N*	*N*
7	*N*	*B, L-M*	*B, L-M*	*B, L-M*	*B, H*	*M, L-M*	*B, H*	*B, L-M*	*N*	*N*
8	*N*	*B, L-M*	*B, L-M*	*B, L-M*	*B, H*	*B, L-M*	*B, H*	*B, H*	*B, H*	*B, H*
9	*C, 0*	*M, 0*	*B, L-M*	*B, L-M*	*B, H*	*B, H*	*B, H*	*B, H*	*B, H*	*B, H*
10	*C, 0*	*C, 0*	*M, 0*	*B, L-M*	*B, L-M*	*B, L-M*	*B, H*	*B, H*	*B, H*	*B, H*

Number of nonforested cells
12 × 2.5 = *30* acres

Number of forested cells by vegetation type and damage class

Conifer
0 *14* × 2.5 = *35* acres
L-M *2* × 2.5 = *5* acres
H *0* × 2.5 = *0* acres

Mixed-wood
0 *4* × 2.5 = *10* acres
L-M *9* × 2.5 = *22.5* acres
H *1* × 2.5 = *2.5* acres

Broadleaf
0 *2* × 2.5 = *5* acres
L-M *28* × 2.5 = *70* acres
H *28* × 2.5 = *70* acres

Total *100* × 2.5 = *250* acres

Figure 5.6. Sample data sheet for recording vegetation/damage class data taken from aerial photos (using codes as defined on page 31). Italics indicate data entered by photo interpreter.

Chlorotic or Yellow Foliage—Broadleaf trees with chlorotic or yellow foliage appear as pink or white (acute chlorosis) on CIR film. These typically occur on steep slopes with shallow, low nutrient soils. This is also typical of beech bark disease, a condition caused by a bark-infesting scale insect followed by fungus invasion. Another possible cause for this signature is early fall coloring of broadleaf trees that typically have yellow autumn foliage.

Conifer Mortality—Groups of dead and dying conifers killed by bark beetles may be seen on CIR photos. Crowns have either a pale yellow-green, yellow, gray, or blue-gray hue. In some cases they may occur mixed with tree crowns of the normal red-brown hue of healthy conifers.

Recent Timber Harvesting Operations—Openings in the forest caused by recent timber harvesting operations can be distinguished from storm damage by the presence of skid trails. These create a dendritic pattern of openings within the harvest unit.

Early Fall Coloring—This may appear on CIR photos as groups of trees with either bright yellow or white foliage, corresponding in nature to red or yellow foliage, respectively. Early fall coloring appears most frequently in low-lying wet areas where the dominant broadleaf tree is often red maple (*Acer rubrum*).

Early Leaf Fall—These areas may appear on some early fall photography as a gray hue with bare crowns visible, but without broken or bent trees.

5.3.3. Data Analysis

Estimates of the area in each of the vegetation/damage classes can be obtained by transferring individual aerial photo sample data from the data sheets to a spreadsheet similar to the one shown in Table 5.5.

For each vegetation/damage class, compute the following statistics (Table 5.5):

1. Average area in photo sample ($\overline{X}$)

   $$\overline{X} = \sum x/n$$

   Where:

   x = Individual photo sample record for each vegetation/damage class
   n = Number of photo samples

2. Sampling fraction (f)

   $$f = a/A$$

   Where:

   a = Area (acres) in sample
   A = Total area in survey

3. Estimated area of vegetation/damage class in stratum (A_s)

   $A_s = a_s/f$

   Where:

   a_s = Total land area in stratum
   f = Sample fraction

Standard deviation, standard error of the mean for each sample vegetation/damage class, and 95 percent confidence limits for the expanded data can be obtained as follows (Table 5.6):

4. Variance (s^2)

   $s^2 = [\sum(x)^2 - (\sum x)^2/n]/(n-1)$

   Where:

   x = Vegetation/damage class
   n = Number of photo sample blocks

5. Standard deviation (s):

   $s = \sqrt{s^2}$

6. Standard error of the mean ($s_{\bar{x}}$):

   $s_{\bar{x}} = \sqrt{((s^2/n) \times (1- (n/N))}$

   Where:

   N = Total possible number of photo sample blocks
   (Total survey area/area per photo sample block)

7. Percent standard error ($\%s_{\bar{x}}$):

   $\%s_{\bar{x}} = (s_{\bar{x}}/\bar{X}) \times 100$

8. 95 percent confidence limits for expanded data:

   $A_s \pm 95\% = A_s \pm \%s_{\bar{x}}/100 \times t_{n-1}$

   (*t* values for n-1 degrees of freedom [df] for a given probability can be obtained from most statistics texts [e.g., Freese 1967] or the table in Appendix B.)

Estimates of the area of each vegetation/damage class can be summarized in a data table such as shown in Table 5.7.

Table 5.6. Summary of statistics derived from data summarized in Table 5.5

Parameter	Vegetation/damage class									
	Nonforested	Conifer 0[a]	Conifer L-M[b]	Conifer H[c]	Mixed-wood 0	Mixed-wood L-M	Mixed-wood H	Broadleaf 0	Broadleaf L-M	Broadleaf H
Total (acres)	1,782.50	3,030.00	170.00	27.50	730.00	362.50	212.50	507.50	440.00	237.50
Average	59.42	101.00	5.67	0.92	24.33	12.08	7.08	16.92	14.67	7.92
n[d]	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
Variance	5,215.81	4,892.93	277.56	9.69	920.66	275.47	184.09	675.29	685.23	181.07
Std deviation	72.22	69.95	16.66	3.11	30.34	16.60	13.57	25.99	26.18	13.46
N[e]	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00	1,000.00
Std error	12.99	12.58	3.00	0.56	5.46	2.98	2.44	4.67	4.71	2.42
% std error	21.86	12.45	52.87	61.07	22.42	24.70	34.44	27.62	32.09	30.56
Expansions[f]										
Area estimate	59,416.67	101,000.00	5,666.67	916.67	24,333.33	12,083.33	7,083.33	16,916.67	14,666.67	7,916.67
95% confidence limits	26,557.03	25,721.90	6,126.25	1,144.73	11,157.54	6,103.14	4,989.20	9,555.76	9,625.80	4,948.14

[a] 0 = undamaged
[b] L-M = light to moderate damage
[c] H = heavy damage
[d] n = number of photo sample blocks
[e] N = total possible number of photo blocks
[f] Based on a total survey area of 250,000 acres, a sample area of 7,500 acres, and a sample fraction of 0.030.

Table 5.7. Sample data summary of area damaged (acres) with 95 percent confidence limits by vegetation/damage class derived from aerial photo sampling of a 250,000-acre area of ice storm damage in western Maine

Vegetation/ damage class	Nonforested	Conifer	Mixed-wood	Broadleaf	Total
None	59,416.67 ±26,557.03	101,000.00 ±25,721.90	24,333.33 ± 11,157.54	16,916.67 ±9,555.76	210,666.70
Light-moderate		5,666.67 ±6,126.25	12,083.33 ±6,103.14	14,666.67 ±9,625.80	32,416.67
Heavy		916.67 ±1,144.73	7,083.33 ±4,989.20	7,916.67 ±4,948.14	15,916.67
Total	59,416.67	107,583.30	43,499.99	39,500.01	250,000.00

6. AIRBORNE VIDEO

Color analog airborne videography using a Panasonic CLE 300 Super-Video Home System (S-VHS) and a GPS interface has been developed for acquisition of data on forest damage by the USDA Forest Service's Forest Health Technology Enterprise Team in Fort Collins, CO (Myhre and others 1992). This system has been acquired and used by Forest Service units nationwide for a variety of applications (Myhre and Silvey 1992).

The following section describes a procedure for rapid assessment of forest damage caused by a storm event using strip sampling with the airborne video system. This procedure can provide the following information:

1. Estimates of area damaged by one or more defined damage classes within specified levels of confidence
2. A map showing the general location of affected areas
3. A basis for stratification of damaged areas for subsequent sampling

6.1. APPROACH

The approach to data acquisition using the S-VHS camera is based on the principle of strip cruising or strip sampling and makes use of procedures developed for estimating forest damage using an operations recorder (Heller and others 1952, Ketcham 1964). Sample strips of video imagery are acquired over a target area of known size. The length of each sample strip and swath width of the imagery or the area of individual frames selected for classification is used to determine sample area and the sample fraction. The video imagery is then viewed on a monitor in the office, and individual frames or line segments are classified according to a specified set of damage strata. The area of each damage class is determined for the sample strip. Means, standard deviations, and standard errors are computed for all sample strips over the target area and expanded by the sample fraction to provide area-wide estimates of damage.

Execution of airborne video strip sample surveys can be divided into four steps:

1. Planning and acquisition
2. Image interpretation
3. Data analysis
4. Map production

6.2. PLANNING AND ACQUISITION

6.2.1. Defining Area to Be Surveyed

Area to be surveyed can be determined either from aerial reconnaissance surveys designed to establish the general boundaries of the damaged area or based on political boundaries (e.g., an entire state, a county or group of counties, or a subregion). If political units encompassing a large land area (several million acres) are used to define the survey area, it may be necessary to break the area down into several logical subunits such as the Forest Inventory and Analysis geographic or survey units.

The land area to be covered by the survey must be known in advance. This can be done by laying out the survey area boundaries on a map of known scale, measuring the average length and width of the survey unit, and computing the area in square miles or acres or both.

6.2.2. Flight Lines

The basic sample unit in an airborne video survey is the flight line or flight strip. Flight lines must be of a known length and swath width.

1. Swath Width—The occurrence of windthrow and bent or broken trees caused by climatic events can be resolved on video imagery of either a 0.25-mile (1,320-ft) or 0.50-mile (2,640-ft) swath width. The narrower swath width will provide better resolution and allow for easier classification of light, scattered damage. A 1/2-mile swath width, on the other hand, will include more land area, thus increasing the sampling fraction. Moreover, the wider swath will include more landmarks, thus allowing image analysts to more easily identify ground locations in the event of a GPS failure.

2. Number and Orientation—A minimum of 30 flight lines should be established over the survey area. These should be oriented perpendicular to the general path of the climatic event. For example, for assessment of damage caused by a severe storm that moved in a west to east direction, orient flight lines north to south. For a hurricane traveling along a south-north path, orient flight lines east to west. Whenever possible, the beginning and end of each flight line should coincide with a point that can easily be identified on the ground, such as a road, power line, or river (Figure 6.1).

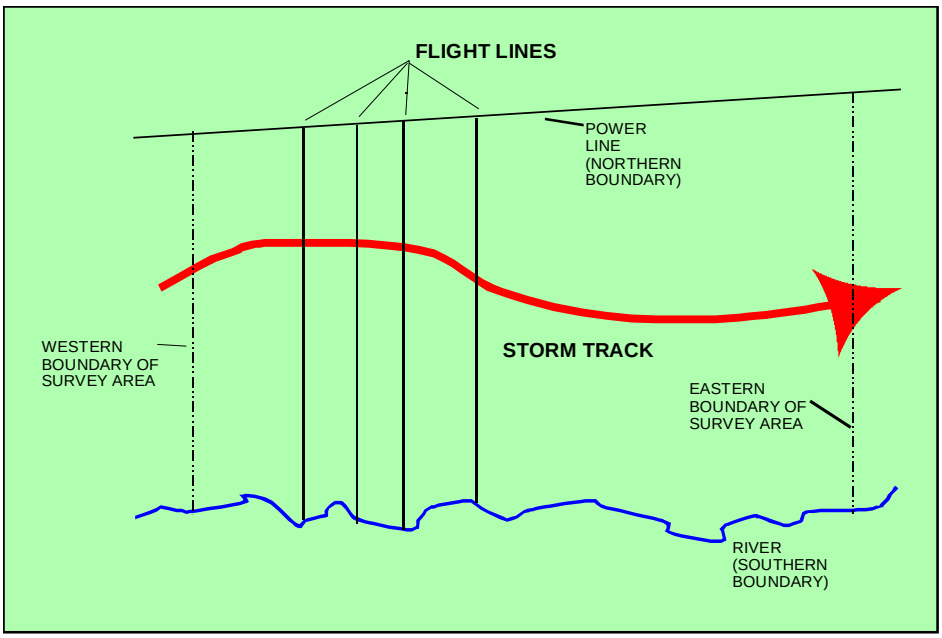

Figure 6.1. Orientation and placement of flight lines relative to a west-east storm track and existing landmarks

3. Distribution—Flight lines may be distributed in either a random, systematic, or semirandom (systematic unaligned) pattern (Figure 6.2). In random flight line selection, all possible flight lines in the survey area have an equal chance of being selected. Systematic flight line placement, on the other hand, locates flight lines at regular intervals (e.g., 1 mile, 5 miles, etc.) throughout the survey area. While statisticians generally prefer a random selection of sampling units, this can result in large gaps over some portions of the survey area and concentrations in other portions. While this should have no effect on area estimates of damage, large irregular gaps between flight lines will make it more difficult to produce a map showing the general location of damaged areas. A compromise between the two approaches is the semirandom or systematic unaligned selection process. This involves subdividing the length of the area to be surveyed into subunits equal to the desired number of flight lines. A flight line is then selected randomly for each subunit.

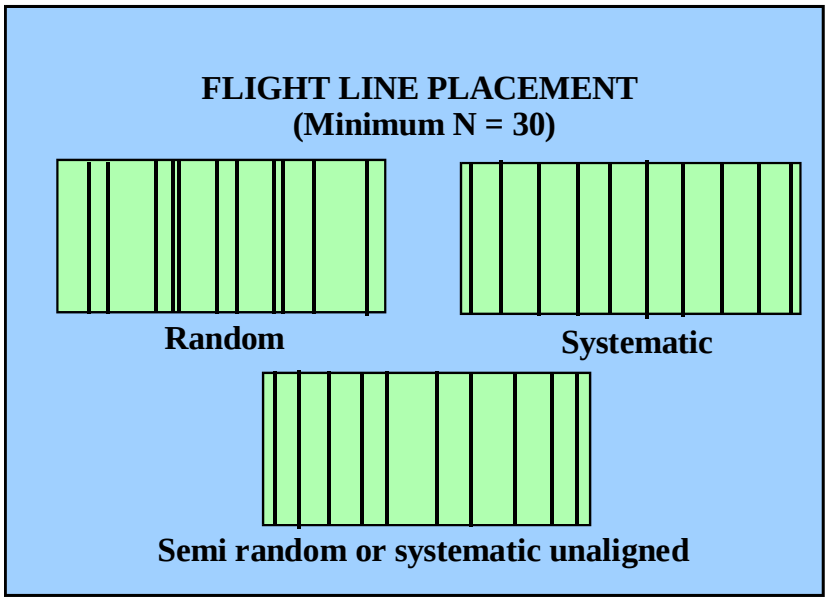

Figure 6.2. Alternative flight line distribution types for an airborne video survey

4. Random Number Generation—Random numbers tables for flight line selection can be taken from a random numbers table in any standard statistical text or generated with spreadsheet software. Formulas for random number generation will vary with software:

In MS Excel the statement is: =rand()
In Corel Quattro Pro the statement is: @rand

For example, to generate random numbers between 1 and 10

In MS Excel, the statement is: =rand()*9+1
In Corel Quattro Pro the statement is: @rand*9+1

To generate random numbers between 0 and 1,000

In MS Excel, the statement is: =rand()*1000

In Corel Quattro Pro the statement is: @rand*1000

If 30 flight lines (swath width = 0.25 miles) are to be randomly selected from a pool of 360 possible flight lines over a distance of 90 miles, use the command:

=rand()*359+1 (Excel) or @rand*359+1 (Quattro Pro)

Type this statement in a cell in your spreadsheet and a random integer between 1 and 360 will appear. Since only whole numbers are needed, make sure that the cell format is set for 0 decimal places. Copy and paste the statement to 29 additional cells in the spreadsheet (five columns of six numbers each) (Table 6.1). Each time this spreadsheet is accessed, a new set of random numbers within the specified limits is generated.

Table 6.1. Thirty-five random numbers between 1 and 360[a]

357	129	186	93	77
68	297	173	149	9
261	176	97	340	144
290	274	261	32	60
38	77	81	168	120
279	268	265	163	33
167	144	197	230	33

[a] The random numbers generated by this process are "with replacement"; therefore, the same number can appear more than once. For example, in this table, the numbers 33 and 261 each appear two times. If sampling without replacement is desired, generate a random numbers table with more than the required numbers (in this case 35 instead of 30) and pass over numbers when they appear more than once.

To facilitate placement of the selected flight lines on a flight map, divide each random number by the swath width fraction to determine the flight line distance in miles and fractions of miles from the survey area boundary. For example, if the swath width is 0.25 miles, divide the random number by 4, if the swath width is 0.5 miles, divide the random number by 2. Results for random numbers selected in Table 6.1 are given in Table 6.2. The numbers can be sorted consecutively using the sort command on spreadsheet software.

Table 6.2. Flight line distances in miles and fractions of miles from survey area boundary based on random number selections in Table 6.1 and a 0.25-mile swath width

89.25	32.25	46.50	23.25	19.25
17.00	74.25	43.25	37.25	2.25
65.25	44.00	24.25	85.00	36.00
72.50	68.50	62.25	8.00	15.00
9.50	19.25	20.25	42.00	30.00
69.75	67.00	66.25	40.75	8.25
41.75	36.00	49.25	57.50	8.25

Draw the flight lines on the map to be used during video acquisition and record the latitude or longitude of each flight line to facilitate data entry into the aircraft's GPS receiver. Also determine the length of each flight line in miles and the land area covered by each flight line in acres[1] (length * swath width/640) (Table 6.3).

[1] 640 acres = 1 square mile

Table 6.3. Flight parameters for an airborne video survey of the 4 July 1999 storm event, Superior National Forest, Minnesota

Flight line	Longitude (degrees, minutes, seconds)	Length (miles)	Total area (acres) (swath width = 0.25 mi)	Number of 30-acre sample points (data capture method 1)	Interval between sample points (seconds) (data capture method 1)
1	91 36 00	20.30	3,248	108	3
2	91 33 00	16.40	2,624	78	4
3	91 30 30	18.00	2,880	89	4
4	91 27 30	18.00	2,880	96	3
5	91 26 30	16.90	2,704	84	4
6	91 25 30	16.90	2,704	89	3
7	91 24 00	16.70	2,672	88	4
8	91 23 15	16.80	2,688	84	4
9	91 19 00	18.00	2,880	84	5
10	91 17 30	18.50	2,960	88	4
11	91 17 00	18.20	2,912	97	4
12	91 16 00	18.60	2,976	92	4
13	91 14 30	18.50	2,960	99	4
14	91 13 45	19.20	3,072	102	3
15	91 13 15	19.00	3,040	80	5
16	91 12 45	20.60	3,296	90	5
17	91 12 30	20.40	3,264	102	4
18	91 12 20	21.20	3,392	113	3
19	91 10 30	21.80	3,488	116	3
20	91 10 00	22.20	3,552	106	4
21	91 08 00	22.80	3,648	121	3
22	91 06 45	24.80	3,968	137	3
23	91 05 30	25.60	4,096	127	3
24	91 03 30	29.00	4,640	136	3
25	90 57 00	28.20	4,512	143	3
26	90 54 30	29.50	4,720	157	3
27	90 49 00	26.40	4,224	122	3
28	90 48 00	25.40	4,064	134	3
29	90 47 30	23.60	3,776	121	3
30	90 46 45	21.60	3,456	112	4
Total			101,2[illegible]	3,1[illegible]	

(Source: Ciesla and others 2000)

6.2.3. Focal Length and Flying Height

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 wide range of flying height and lens focal length combinations can be used to achieve a desired swath width. Selection of the appropriate flying height/lens focal length combination is governed by two factors.

1. Longer lens focal lengths accentuate image movement due to aircraft vibration.
2. Short lens focal lengths maximize variations in swath width caused by changes in terrain elevation.

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

$$h = (D \times f)/I$$

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 1/2-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:

9.5 mm = 0.95 cm/2.54 cm/inch = 0.3740 inches
$h = (D \times f)/I$
$h = (2640 \times 0.3740)/0.3465$
h = 2,849.5 or **2,850 feet AGL**

AGL flying heights for various swath width/focal length combinations are given in Table 6.4.

Table 6.4. Flying height above ground level for selected swath widths and lens focal lengths for airborne video image acquisition

Swath width		Resolution (ft)[a]	Flying height (feet AGL) by lens focal length			
Miles	Feet		9.5mm (0.374 in.)	20mm (0.787 in.)	40mm (1.575 in.)	80mm (3.150 in.)
0.125	660	1.65	712	1,500	3,000	6,000
0.250	1,320	3.30	1,425	3,000	6,000	12,000
0.500	2,640	6.60	2,850	6,000	12,000	24,000
0.750	3,960	9.90	4,275	9,000	18,000	
1.000	5,280	13.20	5,700	12,000	24,000	

[a] Image resolution is determined by dividing swath width in feet by 400 (400 lines on an S-VHS monitor).
(Source: Myhre and others 1992)

6.2.4. Data Acquisition

One of the advantages of video imagery is that it can be acquired under the same weather conditions as aerial sketchmapping.

During the data acquisition phase, video imagery should be taken of the entire flight line.

6.3. IMAGE INTERPRETATION

Image interpretation can begin as soon as some of the video imagery has been acquired (Figure 6.3). Two methods of visual image interpretation have been developed to date for storm damage assessments (Ciesla and others 2000). Equipment required for image analysis includes an S-VHS videocassette recorder and a high resolution color video monitor (minimum size = 10 inches).

Figure 6.3. An image analyst classifies forest damage on airborne video imagery using visual interpretation techniques.

6.3.1. Classification Standards

A variety of damage classification schemes can be used, ranging from a simple two class or binary (no damage/visible damage) to a more complex system with several damage classes (see Table 3.2). Three damage classes were used for an airborne video assessment of storm damage in the Boundary Waters Canoe Area Wilderness of the Superior National Forest in northern Minnesota during 1999 (Figure 6.4) (Ciesla and others 2000). These were adapted from standards used for aerial sketchmapping storm damage as follows (Anon. 1999):

Light damage:	10–33% of trees broken and windthrown
Moderate damage:	34–67% of trees broken and windthrown
Heavy damage:	≥ 68% of trees broken and windthrown

Figure 6.4. Airborne video image of heavy damage caused by the storm of 4 July 1999, Superior National Forest, Minnesota

In addition to an “undamaged” class, if there are significant areas of nonforested land such as lakes, fields, and agricultural or urban lands, it may be desirable to add a “nonforested” class.

6.3.2. Data Recording

Two methods of data recording can be used.

Data capture method 1 involves classification of individual video frames at specified intervals along each flight line. This method requires that the land area covered by a video frame is known. The land area covered by an individual frame of video imagery is determined as follows:

$$A = (W) \times (0.75W) / 43560$$

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 0.25-mile (1,320-ft) swath width is

$$A = (W) \times (0.75W) / 43560$$
$$A = (1320) \times (0.75 \times 1320) / 43560$$
$$A = \mathbf{30\ acres}$$

The land area covered by a video image taken at a 0.50-mile (2,640-ft) swath width is 120 acres. When using this technique, the interval between images can be set to sample as much or as little of the strip as may be required. To make as much use of the 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.

For example, the area of a 20.30-mile, 0.25-mile swath width flight line is 3,248 acres. An aircraft flying at 180 mi/h requires 6.5 minutes to acquire video imagery over that flight line. What should the interval be between single video frames of 30 acres each to capture data for the 3,248 acres?

3248/30 = 108 single video frames to be classified

Lapsed time over flight line = 6.5 minutes × 60 seconds/minute = 390 seconds

390 second/108 frames = 3.6 seconds

Record the GPS latitude or longitude (depending on flight line orientation) as indicated on the image data bank and the lapsed time of the videotape as indicated on the S-VHS VCR of each video frame classified. If more than 50 percent of the land area of a video frame falls into a specified damage class, the entire frame was placed into that class. All data are recorded on the data form shown in Figure 6.5.

Data capture method 2 involves viewing all of the imagery acquired of each flight line and classifying line segments into the specified damage classes. The beginning and end point of each line segment is identified by the time, in minutes and seconds, as indicated on the VCR and by the GPS latitude or longitude, depending on flight line orientation, indicated on the image data bank and recorded on the form shown in Figure 6.6. The lapsed time information for each line segment is converted to minutes and tenths of minutes of each line segment using Table 6.5, and the total times for line segments in each damage class are then added and converted to acres using a simple ratio estimating procedure based on the total land area covered by each flight line.

AIRBORNE VIDEO FLIGHT LINE DATA SUMMARY-METHOD 1

(For classification of scenes at specified time intervals—data capture method 1)

Survey date: *05 Aug 99* State: *MN* Unit: *BWCAW*

Swath width: *0.250 mile* Flight line: *8 N-S* Flight line GPS: *91º23'15"* Flight line length (miles): *16.80*

Plot area (acres): *30* GPS starting point: *48º01'00"* GPS ending point: *48º07'45.3"*

Plot number	Lapsed time (minutes & seconds)	GPS point	Nonforested	Undamaged	Light	Moderate	Heavy
1	*45:10*	*48º01'50"*	*X*				
2	*45:20*	*48º02'25.4"*	*X*				
3	*45:30*	*48º02'54.9"*					*X*
4	*45:40*	*48º03'31.1"*	*X*				
5	*45:50*	*48º04'4.1"*			*X*		
6	*46:00*	*48º04'34.5"*			*X*		
7	*46:10*	*48º05'6.5"*			*X*		
8	*46:20*	*48º05'38.5"*	*X*				
9	*46:30*	*48º06'12.8"*		*X*			
10	*46:40*	*48º06'44.4"*	*X*				
11	*46:50*	*48º07'14.6"*		*X*			
12	*47:00*	*48º07'45.3"*		*X*			
13							
14							
15							
16							
17							
18							
19							
20							
Stratum totals (number of plots)			*5*	*3*	*3*	*0*	*1*
Stratum totals (acres)			*150*	*90*	*90*	*0*	*30*

Figure 6.5. Sample data recording form for classifying damage on individual video frames

AIRBORNE VIDEO FLIGHT LINE DATA SUMMARY-METHOD 2

(For classification of entire flight line by line segments—data capture method 2)

Survey date: *13 Aug 99* State: *MN* Unit: *BWCAW*

Swath width: *0.250 mile* Flight line: *14 N-S* Flight line GPS: *91º13'45"* Flight line length (miles): *19.20*

Flight line area (acres): *3,072* GPS starting point: *48º07'48.7"* GPS ending point: *47º47'59.1"*

Record time over each line segment stratum in minutes and fractions of minutes

Line segment	GPS		Lapsed time		Nonforested or undamaged	Light	Moderate	Heavy	Total
	Start	Stop	Start	Stop					
A-B	48º07'48.7"	48º06'42.7"	34:47	35:54	0.12				
B-C	48º06'42.7"	48º05'28.7"	34:54	35:03			0.15		
C-D	48º05'28.7"	47º50'36.7"	35:03	37:03				2.00	
D-E	47º 50'36.7"	47º49'27.7"	37:03	37:45	0.70				
E-F	47º49'27.7"	47º49'48.7"	37:45	38:01		0.27			
F-G	47º49'48.7"	47º47'59.1"	38:01	40:34	2.55				
G-H									
H-I									
I-J									
J-K									
K-L									
L-M									
M-N									
N-O									
O-P									
P-Q									
Q-R									
Stratum totals (minutes)					3.37	0.27	0.15	2.00	5.79
Stratum totals (percent)					0.5820	0.0466	0.0259	0.3454	1.00
Stratum totals (acres)					1,788.02	143.25	79.59	1,061.14	3,072

Figure 6.6. Sample data form for classifying line segments of video imagery

Table 6.5. Second to portion of minute conversion table

Seconds	Minutes	Seconds	Minutes	Seconds	Minutes	Seconds	Minutes	Seconds	Minutes	Seconds	Minutes
1	0.02	11	0.18	21	0.35	31	0.52	41	0.68	51	0.85
2	0.03	12	0.20	22	0.37	32	0.53	42	0.70	52	0.87
3	0.05	3	0.22	23	0.38	33	0.55	43	0.72	53	0.88
4	0.07	14	0.23	24	0.40	34	0.57	44	0.73	54	0.90
5	0.08	15	0.25	25	0.42	35	0.58	45	0.75	55	0.92
6	0.10	16	0.27	26	0.43	36	0.60	46	0.77	56	0.93
7	0.12	17	0.28	27	0.45	37	0.62	47	0.78	57	0.95
8	0.13	18	0.30	28	0.47	38	0.63	48	0.80	58	0.97
9	0.15	19	0.32	29	0.48	39	0.65	49	0.82	59	0.98
10	0.17	20	0.33	30	0.50	40	0.67	50	0.83	60	1.00

Either data collection technique—classification of individual frames at specified intervals along each flight line or classification of line segments along the entire flight line—will produce acceptable and comparable data. Classification of individual video frames is more time consuming by a factor of about 2.5. This method provides for separation of nonforested areas, especially if these areas are small and scattered. A drawback of the line segment classification technique is that it may be difficult to detect transitions between “no damage” and “light damage” or between “light damage” and “moderate damage.”

6.4. DATA ANALYSIS

Analysis of data derived from strip sampling of airborne video is identical to that described for the aerial photo sampling described in Chapter 5, Section 5.3.3.

The sampling fraction (percent of sample) is the area (in acres) included in the sample divided by the total area included in the survey (see Section 5.3.3, equation 2).

The total area of each damage class is determined for each flight line and transferred from the data sheets entered into a spreadsheet (either Quattro Pro or Excel) (Table 6.6). Means, variances, standard deviations, and standard errors are then computed for each damage class and expanded by the sampling fraction to obtain area estimates (Table 6.7). Confidence intervals are computed according to the equation given in Section 4.3, equation 8 using “*t*” values given in Appendix B. Final data can be summarized in the format provided in Table 6.8.

Table 6.6. Spreadsheet summarizing 30-acre airborne video classifications of storm damage by damage class, Superior National Forest, Minnesota, 1999

Flight line number	Damage class (in acres)									
	Nonforested		Undamaged		Light (10–33%)		Moderate (34–67%)		Heavy (≥ 68%)	
	Area	Area^2	Area	Area^2	Area	Area^2	Area	Area^2	Area	Area^2
1	900	810,000	1,950	3,802,500	60	3,600	0	0	330	10,890
2	690	476,100	1,080	1,166,400	60	3,600	90	8,100	420	176,400
3	660	435,600	1,410	1,988,100	60	3,600	30	900	510	260,100
4	630	396,900	1,440	2,073,600	120	14,400	90	8,100	600	360,000
5	600	360,000	1,440	2,073,600	0	0	60	3,600	420	176,400
6	750	562,500	1,500	2,250,000	120	14,400	60	3,600	240	57,600
7	690	476,100	1,620	2,624,400	30	900	30	900	270	72,900
8	390	152,100	1,740	3,027,600	240	57,600	60	3,600	210	44,100
9	270	72,900	1,560	2,433,600	120	14,400	210	44,100	360	129,600
10	660	435,600	1,350	1,822,500	150	22,500	60	3,600	420	176,400
11	960	921,600	1,170	1,368,900	240	57,600	90	8,100	450	202,500
12	270	72,900	1,170	1,368,900	420	176,400	300	90,000	600	360,000
13	510	260,100	1,530	2,340,900	120	14,400	180	32,400	630	396,900
14	390	152,100	1,620	2,624,400	120	14,400	180	32,400	750	562,500
15	480	230,400	1,350	1,822,500	30	900	120	14,400	420	176,400
16	630	396,900	1,530	2,340,900	0	0	60	3,600	480	230,400
17	630	369,900	1,680	2,822,400	60	3,600	60	3,600	630	396,900
18	810	656,100	1,920	3,686,400	30	900	90	8,100	540	291,600
19	240	57,600	2,220	4,928,400	120	14,400	150	22,500	750	562,500
20	450	202,500	1,950	3,802,500	120	14,400	180	32,400	480	230,400
21	360	129,600	1,860	3,459,600	330	108,900	210	44,100	870	756,900
22	420	176,400	1,980	3,920,400	450	202,500	300	90,000	960	921,600
23	270	72,900	1,980	3,920,400	360	129,600	150	22,500	1,050	1,102,500
24	180	32,400	2,100	4,410,000	330	108,900	90	8,100	1,380	1,904,400
25	690	476,100	2,100	4,410,000	570	324,900	390	152,100	540	291,600
26	720	518,400	2,160	4,665,600	510	260,100	480	230,400	840	705,600
27	360	129,600	1,530	2,340,900	690	476,100	510	260,100	660	435,600
28	450	202,500	1,740	3,027,600	660	435,600	510	260,100	660	435,600
29	180	32,400	1,320	1,742,400	1,020	1,040,400	840	705,600	270	72,900
30	360	129,600	1,380	1,904,400	750	562,500	390	152,100	480	230,400
Total	15,600	9,424,800	49,380	84,169,800	7,890	4,081,500	5,970	2,249,100	17,220	11,829,600
Avg	520.00		1,646.00		263.00		199.00		574.00	

Table 6.7. Summary of statistics derived from data summarized in Table 6.6

Parameter	Damage class				
	Nonforested	Undamaged	Light (10-33%)	Moderate (34-67%)	Heavy (≥ 68%)
Total (acres)	15,600.00	49,380.00	7,890.00	5,970.00	17,220.00
Avg	520.00	1,646.00	263.00	199.00	574.00
Variance	45,268.97	99,666.21	69,187.24	36,588.62	67,080.00
n[a]	30.00	30.00	30.00	30.00	30.00
Std deviation	212.77	315.70	263.03	191.28	259.00
N[b]	166.00	166.00	166.00	166.00	166.00
Std error	35.16	52.17	43.47	31.61	42.80
% std error	6.76	3.17	16.53	15.88	7.46
Expansions[c]					
Area estimate	90,582.54	287,583.24	45,950.42	34,768.57	100,287.23
95% confidence limits	12,562.67	18,640.42	15,530.84	11,294.18	15,292.50
% of area	16.24	51.41	8.21	6.21	17.93

[a] n = number of photo sample blocks
[b] N = total possible number of photo blocks
[c] Based on a total survey area of 559,442 acres, a sample area of 96,060 acres, and a sample fraction of 0.172.

Table 6.8. Estimates of forest damage caused by the 4 July 1999 storm, video demonstration site, Superior National Forest, Minnesota, using data collection method 1[a]

Damage class	Area affected (acres)	95% confidence limits	% of area
Nonforested[b]	90,852.54	± 12,562.67	16.24
Undamaged	287,583.24	± 18,640.42	51.41
Light damage (10–33%)	45,950.42	± 15,530.84	8.21
Moderate damage (34–67%)	34,768.57	± 11,294.18	6.21
Heavy damage (≥ 68%)	100,287.23	± 15,292.50	17.93
Total area	559,442.00	--	100.00

[a] Based on a sampling fraction of 17.2%
[b] Includes lakes and sphagnum bogs
(Source: Ciesla and others 2000)

6.5. MAP PRODUCTION

Maps showing the general location of damage can be produced by transferring areas of light, moderate, and heavy damage along each flight line to a map base using the GPS data recorded for each sample point or the beginning and end of each classified line segment. Lines can then be drawn between the flight lines to connect areas of the same damage class (Figure 6.7 and Figure 6.8).

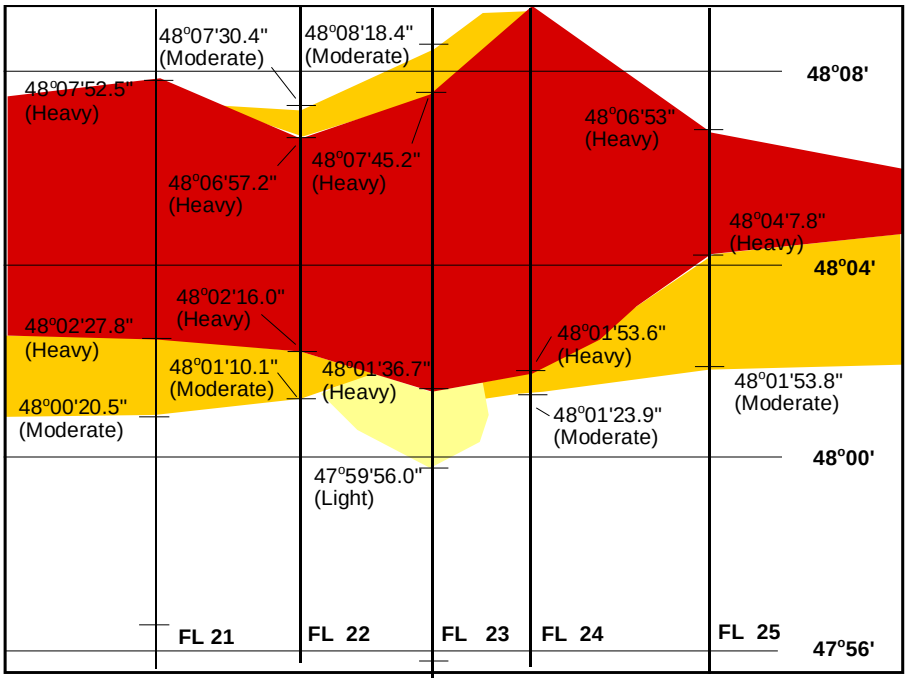

Figure 6.7. Damaged areas classified from a portion of video imagery obtained over a storm-damaged area on the Superior National Forest, Minnesota, plotted on a map base using GPS data. This map can be produced from data generated by either data capture method 1 or 2.

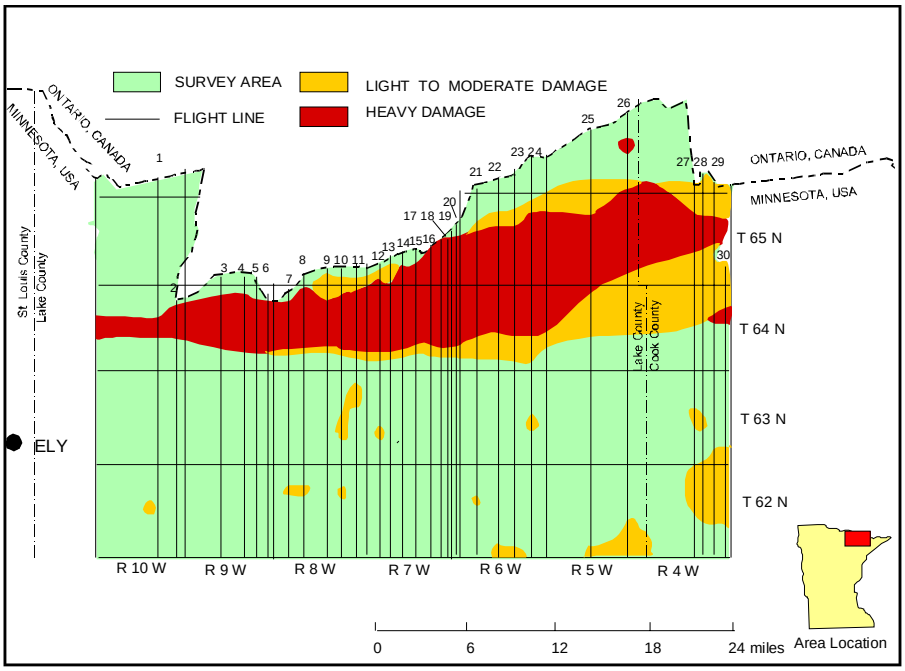

Figure 6.8. Map of forest damage caused by the 4 July 1999 storm derived from analysis of airborne video imagery, Superior National Forest, Minnesota. This map can be produced from data generated by either data capture method 1 or 2.

6.6. LIMITATIONS

Strip sampling with airborne video, as developed to date, is recommended for use in areas of relatively level terrain. Abrupt changes in ground elevation typical of mountainous terrain will result in changes in flight line swath width. While use of a combination of a longer lens focal length and increased AGL flying height will reduce variations in swath width due to changes in terrain elevation, it is not sufficient to compensate for the magnitude of ground elevation change encountered in rugged mountain terrain. The data collection method that classifies individual video frames at specified intervals along each flight line could be adapted to mountainous terrain by computing the area covered by each frame selected for classification based on the ground elevation and AGL flying height of that specific image. This concept has not yet been tested, however.

7. SUPPLEMENTAL GROUND SURVEYS

Ground surveys are usually an integral part of remote sensing. In their simplest form, supplemental ground surveys are done to verify classifications made from remote sensing. Ground surveys may also be used in conjunction with remote sensing in multistage or multiphase sampling designs to provide additional information not readily obtainable via remote sensing. Examples include characterization of damage classes defined by remote sensing in terms of tree species and timber volume affected, fuel loading, hazard of pest outbreaks, and related information.

7.1. HOW ESSENTIAL ARE GROUND SURVEYS?

While ground surveys are desirable in all surveys and assessments involving remote sensing and should be carried out if at all possible, they are not always essential. Moreover, ground surveys are time consuming and may not always be possible within the time frame data are required to support an emergency response. Ground surveys following climatic events have an added logistical challenge in that severe windthrow and breakage can significantly reduce the accessibility of forests (Figure 7.1). Consequently ground surveys in forests affected by catastrophic climatic events will be even more time consuming than surveys in undamaged forests.

Figure 7.1. Ground surveys in forests damaged by catastrophic climatic events are especially time consuming because windthrow and related damage can make walking from sample point to sample point difficult (Bartlett Experimental Forest, White Mountain National Forest, New Hampshire, following the ice storm of January 1998).

There have been instances where rapid assessments of catastrophic climatic events have been conducted successfully with a minimum of ground surveys because the damage signatures were highly visible from the air and the surveys were conducted by people experienced in

aerial observation. Examples include the mapping of forest damage caused by Hurricane Camille in Mississippi in 1969 (Terry and others 1969) and mapping of the 4 July 1999 storm in northern Minnesota (Anon. 1999).

More formal ground surveys may be carried out long after data needs for initial emergency responses are satisfied to obtain more detailed information on the overall impacts of the damage. For example, when Hurricane Hugo struck South Carolina in 1989, aerial and informal ground surveys by the South Carolina Forestry Commission provided the immediate information needed to guide salvage operations of damaged timber, establish fire control measures, and do initial planning for reforestation. Longer-term information requirements, such as changes in wood supply, needed shifts in wood procurement by forest industry, and adjusting long-term resource management programs were met by a special inventory of forest resources in the damaged area conducted by the Forest Inventory and Analysis unit of the USDA Forest Service's Southeastern Forest Experiment Station. This was accomplished by revisiting 2,530 permanent plots in the 23 counties affected by the hurricane (Sheffield and Thompson 1992). Similarly, 1,724 survey plots were visited in Maine, New Hampshire, Vermont, and New York following the ice storm of January 1998 to provide more detailed estimates of forest damage caused by that event (USDA Forest Service 1998). These more intensive surveys are beyond the scope of this manual.

7.2. ACCURACY ASSESSMENT

One of the objectives of ground surveys is to assess the accuracy of classifications made from remote sensing. This can be done by visiting a small sample of sites classified by remote sensing on the ground, classifying the damage according to the same standards as used during the remote sensing phase, and comparing the two independent classifications in an error matrix. Sites examined on the ground could be damage polygons classified by sketchmapping, 2.5-acre plots classified on aerial photos, or individual frames of video imagery.

7.2.1. Field Observations

For each primary political or administrative stratum (e.g., state) select approximately 100 sites for ground examination. The sites selected should be forest stands of at least 25 acres in size and represent roughly equal numbers of each damage stratum as classified by remote sensing. For example, if a three damage class system (e.g., no visible damage, light-moderate damage, heavy damage) is used, approximately one-third of the sites should be areas classified as no visible damage, light-moderate damage, and heavy damage, respectively.

Use existing roads and trails to access the selected sites and establish anywhere from 3 to 10 observation points to classify the damage. Classify each observation point and the entire stand using the same classification standards as used for remote sensing. Also record the GPS coordinates of the approximate centroid of each site.

7.2.2. 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 (e.g., pixels, clusters, polygons) assigned to a particular category in one classification (e.g., remote sensing) relative to the number of sample units assigned to a particular category in another classification (e.g., ground surveys). In most cases, one set of

classifications is considered to be correct or relatively 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 matrix shown in Table 7.1 show the agreement between classification of forest damage by remote sensing into three classes—none, light to moderate (L-M), and heavy—compared with a reference data set developed from ground surveys of the same sites. The cell values represent 100 sample points at which each aerial observer's classification was compared with the reference data.

Table 7.1. Error matrix of a hypothetical comparison between remote sensing and ground based reference data of forest damage

	Ground survey reference data					
Aerial sketchmap data	**Class**	**None**	**L-M[a]**	**Heavy**	**∑ rows**	**Commission error (%)**
	None	**35**	4	2	41	14.6
	L-M	4	**25**	6	35	28.6
	Heavy	0	9	**15**	24	37.5
	∑ columns	39	38	23	100	
	Omission error (%)	10.3	34.2	34.8		

[a] L-M = light-moderate

∑ main diagonal = 75 Chance agreement (%) = 34.8
Observed agreement (%) = 75 Kappa (κ) = 0.617

Once the data are arrayed in individual cells as displayed in Table 7.1, some simple statistics can be computed for the error matrix. The percent correct classification, or observed agreement, is the sum of the correct classifications in the diagonals divided by the total number of observations. For example, in Table 7.1 the observed agreement is:

35 + 25 + 15 = 75/100 = 0.75 or **75%**

In remote sensing, there are two basic types of classification errors. Omission error is the error associated with not classifying an entity into a class when, in fact, it should be classified. Commission error is the error associated with classifying an entity into a class when it should not be in that class.

Omission and commission errors can be determined for each class in the error matrix (Lo and Watson 1998). Omission error is the sum of the nondiagonal cell values (those that indicate no agreement) for the reference data (columns in Table 7.1) divided by the column total. In the error matrix shown in Table 7.1, omission error for the L-M class is determined as follows:

4 + 9 = 13/38 = 0.342 or **34.2%**

Commission error is the sum of the nondiagonal cell values for the test data (rows in Table 7.1) each row divided by the row total. Again, for the error matrix in Table 7.1, commission error for the L-M class is:

4 + 6 = 10/35 = 0.286 or **28.6%**

7.2.3. 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. Chance agreement equates to 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, 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 7.1 is:

$39 \times 41 = 1599/100 = 16.0\%$
$38 \times 35 = 1330/100 = 13.3\%$
$23 \times 24 = 552/100 = 5.5\%$

Chance agreement for this error matrix is:

16.0 + 13.3 + 5.5 = **34.8%**

Kappa or κ for this error matrix is:

(0.75 - 0.348)/(1 - 0.348) = **0.617**

The value of κ ranges between +1 and -1. Since there is, at least theoretically, a positive correlation between remote sensing and reference data, positive values of κ are expected. An interpretation of the values of κ given by Landis and Koch (1977) is:

Strong agreement:	$\kappa > 0.80$
Moderate agreement:	$\kappa \geq 0.40$ and ≤ 0.80
Poor agreement:	$\kappa < 0.40$

7.3. CHARACTERIZATION OF DAMAGE STRATA

Another objective of ground data acquisition is to characterize damage to forest resources in areas identified by remote sensing in terms such as tree species affected, volume loss, and fuel loading. The protocol described in the following sections was developed to characterize damage to forests following the ice storm of January 1998 in the northeastern United States and is based on protocols developed for forest health assessments (Ice Storm Damage Assessment Group and Ciesla 1998).

7.3.1. Sample Plots

The basic sample unit is a variable radius plot presently used in the Northeast for Forest Health Monitoring and Forest Inventory and Analysis.

1. For trees ≥ 5 inches d.b.h. use a 24-foot radius plot.
2. For trees < 5 inches d.b.h. use a 6.8-foot radius microplot nested within the larger plot, with the center of the microplot offset at a 90-degree azimuth and 12 feet from plot center.

7.3.2. Number and Distribution of Sample Plots

For aerial sketchmap surveys, select about 10 to 15 damage polygons mapped for each major political unit in the survey area (e.g., state, county, forest survey unit). Polygons should be evenly distributed among the damage classes and should represent the various physiographic and vegetation conditions within the unit. Areas with reasonable road or trail access should be used to facilitate survey teams. Five to 10 sample plots should be established in a transect across the longest axis of the damage polygon according to the following guidelines.

Area of polygon	Number of sample plots
Up to 500 acres	5
500 to 1,000 acres	6–8
> 1,000 acres	10

For the aerial photo sampling method described in Chapter 4, Section 4.3, establish one sample plot near the center of each 2.5-acre photo cell selected for ground survey.

The number of 2.5-acre photo cells to be sampled per damage class in each vegetation type are:

Damage class	Sampling rate
No damage	Approximately 1%
Light-moderate	Approximately 2–5%
Heavy	Approximately 5–10%

7.3.3. Data Elements

The following data elements, consistent with Forest Health Monitoring (FHM) and Forest Inventory and Analysis (FIA) protocols, should be recorded on a data form similar to that shown in Figure 7.2.

1. Site — Record location details, elevation, aspect, and forest type (use FIA forest type codes).
2. Fire hazard — Estimate within a 60-foot radius of plot center. Include fuel load (high, medium, low, or none) and fuel type (based on percent hardwood and softwood slash).
3. Species — Record tree species using FIA species codes.

FIELD DATA SHEET
DAMAGE STRATUM CHARACTERIZATION SURVEY

Page _____ of _____

State:_____ Quad name: _____ Sample point: _____ Field crew:_____

Location (GPS): Latitude:_____ Longitude:_____ Fire hazard:_____

Elevation:_____ Aspect:_____ Forest type:_____

Species	D.b.h.	Crown position	Stem condition	Crown damage (%)	Bole condition	Tree condition	Tree height

Figure 7.2. Sample data form for field characterization of damage strata classified from remote sensing

4. D.b.h. — Record diameter for all trees ≥ 5 inches d.b.h. to the nearest 2-inch diameter class. Within the microplot, only 2-inch class (1.0–2.9 inches) and 4-inch class (3.0–4.9 inches) trees will be tallied.

5. Crown position — Record tree crown position according to FIA system:
   1 = open grown
   2 = dominant
   3 = codominant
   4 = intermediate
   5 = overtopped

6. Stem condition
   1 = bent or leaning ≥ 45 degrees
   2 = bent or leaning ≥ 45 degrees with crown touching the ground
   3 = uprooted

7. Crown damage — Estimate amount of crown broken/removed due in particular to ice damage in 10% classes beginning with 0% (no breakage) to 100% (entire crown broken). Include branches that are broken but still attached. Do not include older, previously broken branches or dieback (Cox 1998).

8. Bole condition
   1 = bole broken below the crown
   2 = bole severely split below the crown

9. Tree condition — Record obvious pest damage (i.e., beech bark disease) using FHM/FIA special damage codes.

10. Tree height — Estimate total tree height.

7.4. LINKING REMOTE SENSING AND GROUND DATA

Data acquired via remote sensing and ground observations can be linked using several statistical procedures that are an integral part of multistage or multiphase sampling (see Chapter 5, Section 5.3). The simplest form of multistage sampling is double sampling. This involves a large remote sensing sample and a small ground sample. The ground sample is used to adjust the data obtained by remote sensing and/or provide estimates of parameters that cannot be easily obtained via remote sensing, such as tree volumes, fuel loading, or effects on understory vegetation.

Two multistage approaches in which remote sensing and ground data are combined have been used for various forest health assessments including inventories of tree mortality caused by bark beetles and assessment of forest decline. One approach is double sampling with regression, a process that uses a small ground sample to adjust estimates made from remote sensing using a linear regression equation and is described in detail by Wear and others (1966). In probability proportional to size (PPS) sampling, ground samples are selected based on the occurrence of the entity of interest (e.g., occurrence of bark beetle infested trees). Estimates made by remote sensing are corrected based on ground data and the probability of a certain ground sample point being selected. An application of the PPS procedure for adjusting aerial photo estimates of bark beetle infested trees is described by White and others (1983). Neither of these procedures have been applied to assessments of damage caused by climatic events because ground surveys are especially time consuming following these events due to limited accessibility caused by the damage.

8. SUMMARY AND CONCLUSIONS

Remote sensing is a viable and efficient approach for rapid assessment of forest damage caused by catastrophic climatic events such as hurricanes, tornadoes, and ice storms. The use of remote sensing, as opposed to ground surveys, is especially attractive because data are needed in a short time frame and because windthrow and other types of damage associated with these events tend to make forests less accessible.

Planning is the obvious first and critical step in the conduct of forest damage assessments following catastrophic climatic events. This is especially true because when large, multistate areas are affected, the responsibility for damage assessment is shared between several states and the Federal government, and a large number of personnel are involved. Of particular importance is the establishment of damage classification standards that are understood and adhered to by all aerial observers and image interpreters.

This manual outlines survey procedures for rapid assessment of forest damage caused by catastrophic climatic events using aerial sketchmapping, aerial photos, and airborne video with or without accompanying ground surveys. Examples of data analysis procedures and sample data products are given. Because of differences in damage signatures, intensity and types of land uses, data requirements, and the time element within which the data are required, no single survey method will meet the needs of all forest damage surveys. The intent of this manual is to serve as a reference guide that provides several methods for conducting these assessments. Forest health specialists must use their expertise, experience, and knowledge of local conditions to select the most appropriate methods for specific locations, data requirements, and damage types.

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APPENDIX A: SAMPLE DATA FORMS

AERIAL PHOTO 2.5-ACRE GRID CELL VEGETATION TYPE/DAMAGE CLASSIFICATION

State:_____ Subregion:_____ Project:_____

Photo Plot: _____ Date:_____ Photo Interpreter: _____

	A	B	C	D	E	F	G	H	I	J
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

Number of nonforested cells

___ × 2.5 = ___ acres

Number of forested cells by vegetation type/damage class

Conifer

0 ___ × 2.5 = ___ acres
L-M ___ × 2.5 = ___ acres
H ___ × 2.5 = ___ acres

Mixed-wood

0 ___ × 2.5 = ___ acres
L-M ___ × 2.5 = ___ acres
H ___ × 2.5 = ___ acres

Broadleaf

0 ___ × 2.5 = __ acres
L-M ___ × 2.5 = __ acres
H ___ × 2.5 = __ acres

Total ___ × 2.5 = ___ acres

AIRBORNE VIDEO FLIGHT LINE DATA SUMMARY-METHOD 1

(For classification of scenes at specified time intervals—data capture method 1)

Survey date: _____ State: _____ Unit: _____

Swath width: _____ Flight line: _____ Flight line GPS: _____ Flight line length: _____

Plot area (acres): _____ GPS starting point: _____ GPS ending point: _____

Plot number	Lapsed time (minutes & seconds)	GPS point	Nonforested	Undamaged	Light	Moderate	Heavy
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							
Stratum totals (number of plots)							
Stratum totals (acres)							

AIRBORNE VIDEO FLIGHT LINE DATA SUMMARY-METHOD 2

(For classification of entire flight line by line segments—data capture method 2)

Survey date:_____State:_____Unit:_____

Swath width:_____Flight line:_____Flight line GPS: _____Flight line length (miles):_____

Flight line area (acres):_____GPS starting point:_____ GPS ending point:_____

Record time over each line segment stratum in minutes and fractions of minutes

Line segment	GPS		Lapsed time		Nonforested or undamaged	Light	Moderate	Heavy	Total
	Start	Stop	Start	Stop					
A-B									
B-C									
C-D									
D-E									
E-F									
F-G									
G-H									
H-I									
I-J									
J-K									
K-L									
L-M									
M-N									
N-O									
O-P									
P-Q									
Q-R									
Stratum totals (minutes)									
Stratum totals (percent)									
Stratum totals (acres)									

FIELD DATA SHEET
DAMAGE STRATUM CHARACTERIZATION SURVEY

Page _____ of _____

State:_____ Quad name: _____ Sample point: _____ Field crew:_____

Location (GPS): Latitude:_____ Longitude:_____ Fire hazard:_____

Elevation:_____ Aspect:_____ Forest type:_____

Species	D.b.h.	Crown position	Stem condition	Crown damage (%)	Bole condition	Tree condition	Tree height

APPENDIX B: ABBREVIATED TABLE OF THE DISTRIBUTION OF *t*

Degrees of freedom (df)	Probability			
	0.1 (90%)	**0.05 (95%)**	**0.01 (99%)**	**.001 (99.9%)**
1	6.314	12.706	63.657	636.619
2	2.920	4.303	9.925	31.598
3	2.353	3.182	5.841	12.941
4	2.132	2.776	4.604	8.610
5	2.015	2.571	4.032	6.859
6	1.943	2.447	3.707	5.959
7	1.895	2.365	3.499	5.404
8	1.860	2.306	3.355	5.041
9	1.833	2.262	3.250	4.781
10	1.812	2.228	3.169	4.587
11	1.796	2.201	3.106	4.437
12	1.782	2.179	3.055	4.318
13	1.771	2.160	3.012	4.221
14	1.761	2.145	2.977	4.140
15	1.753	2.131	2.947	4.073
16	1.746	2.120	2.921	4.015
17	1.740	2.110	2.898	3.965
18	1.734	2.101	2.878	3.922
19	1.729	2.093	2.861	3.883
20	1.725	2.086	2.845	3.850
21	1.721	2.080	2.831	3.819
22	1.717	2.074	2.819	3.792
23	1.714	2.069	2.807	3.767
24	1.711	2.064	2.797	3.745
25	1.708	2.060	2.787	3.725
26	1.706	2.056	2.779	3.707
27	1.703	2.052	2.771	3.690
28	1.701	2.048	2.763	3.674
29	1.699	2.045	2.756	3.659
30	1.697	2.042	2.750	3.646
40	1.684	2.021	2.704	3.551
60	1.671	2.000	2.660	3.460
120	1.658	1.980	2.617	3.373
∞	1.645	1.960	2.576	3.291

(adapted from Freese 1967)