# Assessing Insect-Induced Tree Mortality Across Large Areas With High-Resolution Aerial Photography in a Multistage Sample

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## Abstract

In recent years, unprecedented tree mortality has occurred throughout the national forests owing to insect infestations and disease outbreaks. The magnitude and extent of mortality, coupled with the lack of routine monitoring in some areas, has made it difficult to assess the damage, associated ecological impact, and fire hazard in a timely and cost-effective manner. To aid forest managers in assessing the damage, a cost-effective multistage sampling method, using high-resolution digital aerial photography, was developed to estimate overall mortality across large areas. The method was tested within a 332,000-acre piñon/juniper woodland west of Flagstaff, Arizona, within the Kaibab National Forest. Piñon pine mortality caused by piñon ips bark beetles (*Ips confusus* (LeConte)) was assessed from high-resolution digital aerial imagery within percent-cover strata with the use of a digital dot grid. The sample revealed that dead trees covered 7.0 ± 0.3 percent of the study area. As a percentage of total tree cover, 20.0 ± 0.8-percent mortality had occurred. The cost to obtain this estimate was approximately $0.04 per acre.

Keywords: Dot grid, imagery, *Ips confusus*, pinyon, remote sensing, sample.

## Introduction

Over the past century, stand density and fuel loading have increased in forests and rangelands throughout the United States, leading to a general decline in ecosystem health. The weakened condition of the forests and rangelands, coupled with drought stress in the Western United States, now place nearly 200 million acres of Federal forest and rangeland in the contiguous United States at risk of epidemic insect and disease outbreaks and catastrophic wildfires (USDA and USCI 2004). In many areas, devastating wildfires and unprecedented insect and disease outbreaks have already occurred.

To address the threat and impact of fire, insects, and diseases to the Nation's forests and rangelands, the U.S. Federal Government launched the Healthy Forests Initiative (HFI) in 2002 and enacted the Healthy Forests Restoration Act (HFRA) in 2003. Primary goals of the HFI and HFRA are to facilitate, expedite, and provide national guidance on hazardous-fuel reduction and ecosystem restoration. In areas where insects and diseases have already caused extensive tree mortality, the HFRA calls for accelerated information gathering on the impact of these mortality agents (USDA and USDI 2004). However, collecting information on the extent and severity of mortality in a timely and cost-effective manner can be very difficult because of the vast acreages that are affected, coupled with the lack of routine monitoring in some areas. In some cases, the extent of mortality is so great that even traditional assessment methods such as aerial sketch-mapping become impractical in terms of time and cost. An efficient and cost-effective alternative assessment method is needed.

One possible alternative is to sample rather than map mortality. Unlike aerial sketch-mapping, which produces a map, but no quantitative measure of mortality, a sample provides a quantitative measure of mortality, but no map. Not all sample designs are efficient or cost-effective, but some have the potential to be less costly and time consuming than traditional methods of assessing mortality. A multistage sample, for example, is one type of sample design

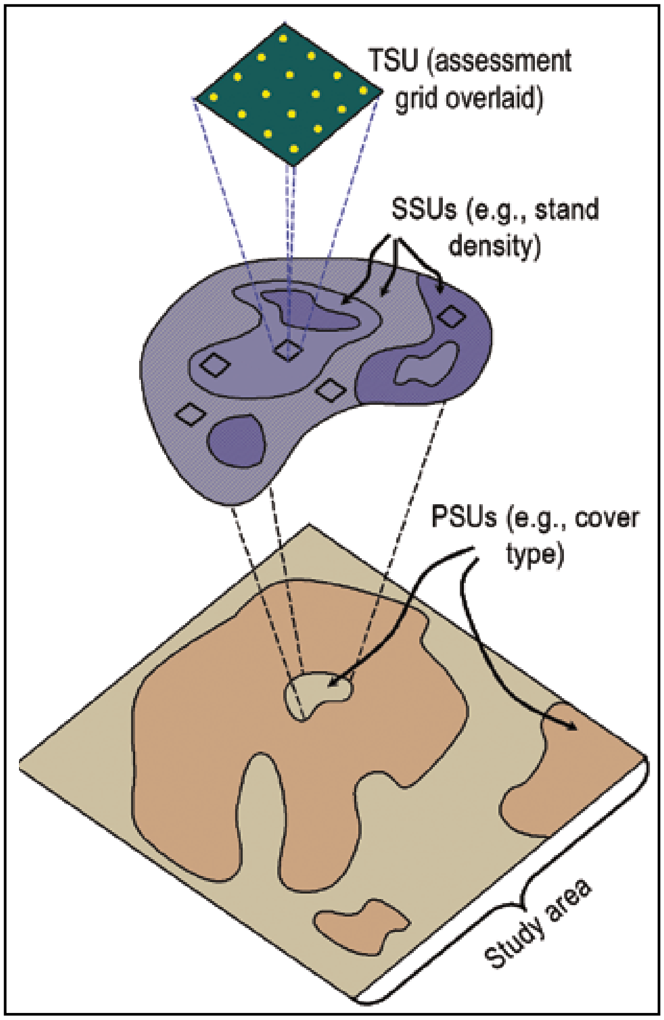


Figure 1—A common multistage sample design defines final sampling units in three consecutive stages: primary sampling units (PSUs), secondary sampling units (SSUs), and tertiary sampling units (TSUs).

that attempts to optimize sampling efficiency. Sampling efficiency is increased by constraining final sampling units to fall within only certain subsections or regions of a study area rather than distributing them across the entire area. Assessing groups or clusters of sample locations is generally easier and less time consuming than assessing widely dispersed sample locations.

In a multistage sample design, a study area is initially partitioned into coarse subunits, called primary sampling units (PSUs). A subset of PSUs is selected and subdivided into secondary sampling units (SSUs). This process of selecting and further subdividing sampling units may be repeated as often as necessary, but a three-stage design is common (Figure 1). In the final stage of the sample, a subset of the previous stage's sampling units are selected and sampled or assessed. From these samples, the variable of interest can be estimated for the entire study area (Ciesla 2000, Schreuder and others 2004).

The dimensions and layout of sampling units can be arbitrary; however, it is generally advantageous to use strata correlated with the variable of interest as sampling units, particularly in the early stages of the design. Sampling within wisely chosen strata allows a multistage sample to take advantage of known sources of variability in the population and can greatly increase the precision of the estimate. When assessing tree mortality, possible strata might include cover type, stand density, elevation, slope, aspect, soil type, proximity to water, and others.

Multistage sample designs have been used previously to inventory timber, estimate tree mortality and volume loss caused by insects in conifer forests, and estimate tree mortality caused by diseases (Ciesla 2000, Langley 1971, Munson and others 1985, White and others 1983). Ciesla (2000) reviewed an assortment of aerial photography-based multistage forest inventories. Typically, these inventories used vegetation type or tree mortality or both as initial-stage strata. Mortality strata were obtained by aerial sketch-mapping or from complete coverage aerial photography. Subsequent stages in these surveys involved collecting aerial photography over plots within the PSU strata. In most of the surveys, the third stage consisted of further subdividing the SSUs into tertiary sampling units (TSUs). A subset of the TSUs was then ground sampled.

Although samples are less costly and time consuming than censuses, multistage samples based on aerial photography and manual photo interpretation can still be expensive and time consuming. Replacing traditional aerial photography in multistage samples with digital aerial and satellite imagery can potentially reduce survey time and related costs. The cost of digital imagery continues to decrease, and economical, yet powerful computers and image processing software can now automate some of the tasks traditionally done by hand. In addition, some field assessments can be greatly reduced by analyzing very high-resolution imagery acquired over the final sampling units.

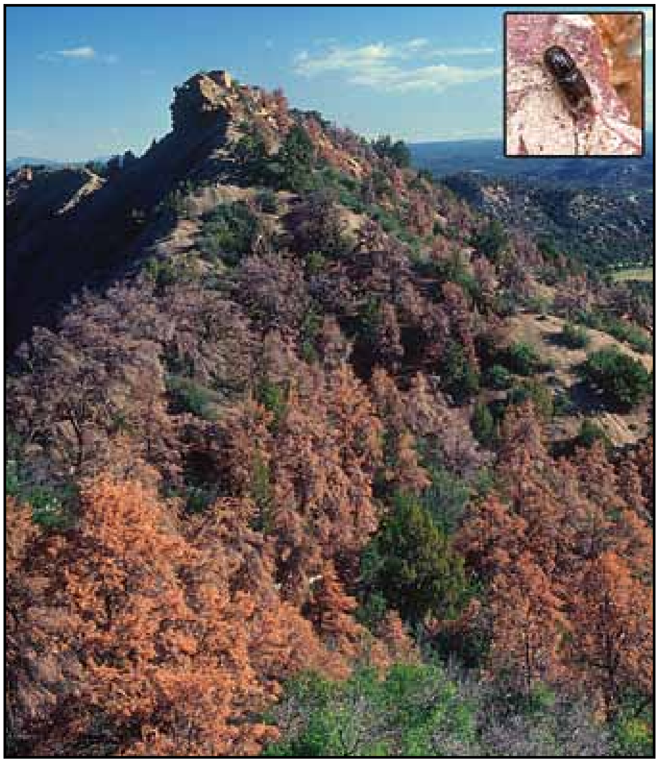

Figure 2—Piñon pine mortality caused by piñon ips beetles (see inset). (Photograph courtesy of William M. Ciesla, Forest Health Management International, Bugwood.org)

To aid forest managers in assessing the severity and extent of widespread tree mortality, the USDA Forest Service Remote Sensing Steering Committee sponsored a pilot study to develop a cost-effective, rapid, and statistically rigorous multistage sample design incorporating digital remotely sensed imagery to quantify tree mortality across large geographic areas. The method was evaluated in a piñon pine/juniper woodland.

## Case Study—Assessing Piñon Pine Mortality

Beginning around 2002, extensive piñon pine (especially *Pinus edulis* Engelm. and *P. monophylla* Torr. & Frem.) mortality appeared throughout the Western United States. Dense stocking and sustained drought weakened the defenses of the pines, making them highly susceptible to attack by piñon ips bark beetles (*Ips confusus* (LeConte)) and other insects, as well as infection by black stain root disease (*Leptographium wageneri* (Kendrick) Wingfield) and other disease agents. Insect feeding and diseases destroy and clog the conductive tissues of the trees, causing them to die. The piñon ips beetle, the most important mortality-causing agent of the recent mortality event, is a native species that typically plays an important role in maintaining healthy forests by removing stressed or injured trees. This process thins the forest and reduces competition for water, nutrients, and light. Healthy trees are generally unaffected by the beetles. However, the abundance of drought-weakened trees allowed beetle populations to explode, causing extensive mortality in stressed and healthy trees throughout the piñon/juniper range (Figure 2) (Keyes and Hebertson 2003, Negron and Wilson 2003, Shaw and others 2005).

Because piñon/juniper woodlands are not routinely monitored, assessing the ecological impact of the mortality and the fire hazard it presented became very difficult. Therefore, a rapid and cost-effective multistage sample design incorporating digital aerial imagery was developed to assess tree mortality.

### Methods

A multistage sample design was developed and evaluated in a study area located west of Flagstaff, Arizona, in and around the Williams Ranger District of the Kaibab National Forest. The footprint of a SPOT 5 satellite image (60 by 60 km) provided the approximate geographical boundary for the study (Figure 3). In this region, a mixture of piñon pine and juniper (*Juniperus* sp.) dominates lower elevations whereas the upper-elevation forests are predominantly ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) interspersed with aspens (*Populus tremuloides* Michx.) and higher-altitude conifers.

**Stage 1—Piñon/Juniper Woodland Cover Type (PSUs)—** The first stage of the multistage sample design consisted of locating the piñon/juniper cover type within the study area to eliminate non-piñon/juniper areas from further analysis. Existing cover-type maps (i.e., from the Gap Analysis Program, the Rocky Mountain Resource Information System, the National Landover Data set, and other sources) were evaluated for this purpose. These data sets were deemed unsatisfactory for this study because changes in cover type from vegetation management activities were sometimes not

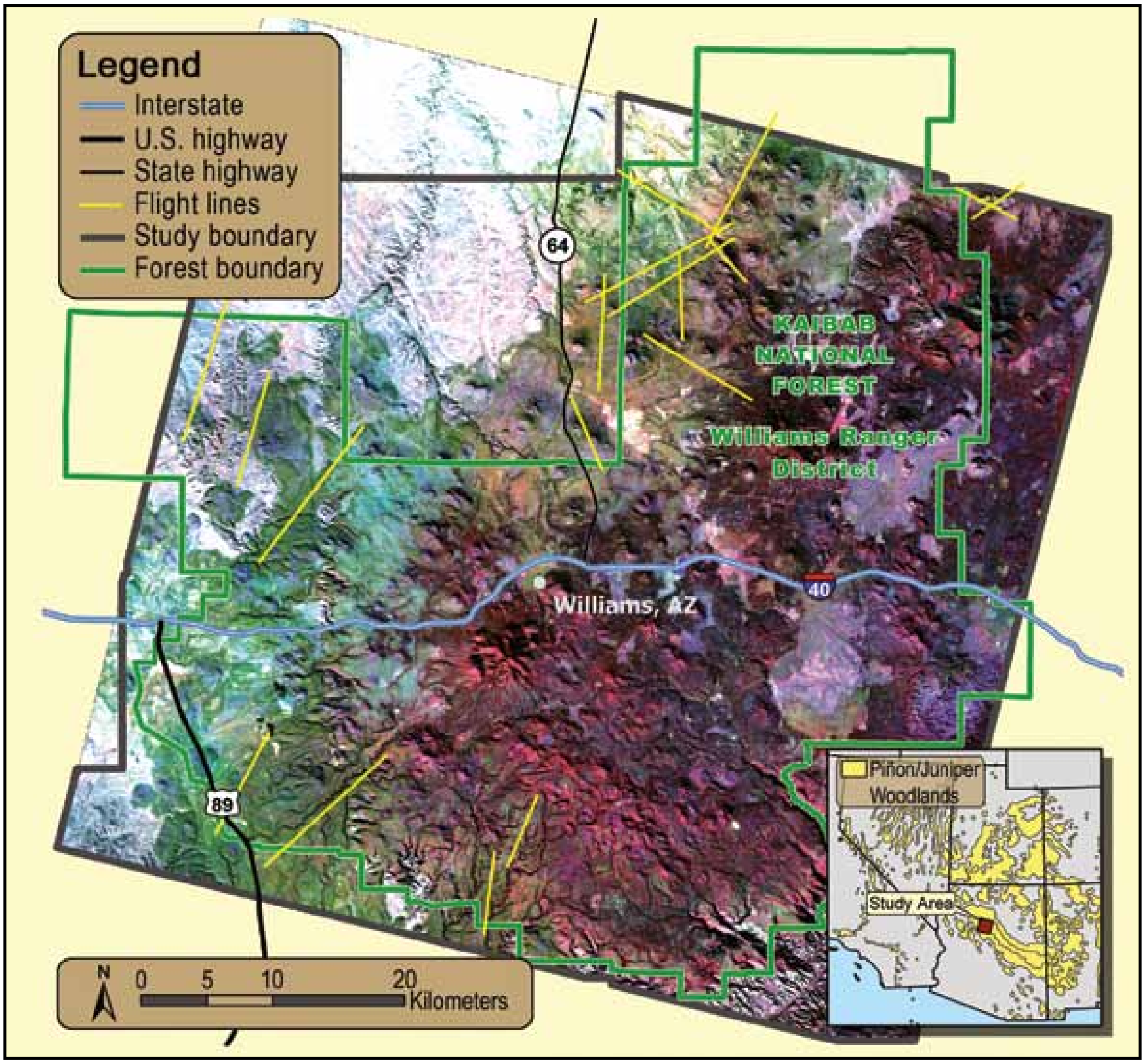


Figure 3—The pilot study area was located west of Flagstaff, Arizona, within the Williams Ranger District of the Kaibab National Forest. A SPOT 5 satellite imagery scene (acquired September 16, 2003)—displayed in false color infrared with topographic enhancement—defined the extent of the study area. Green and blue/green areas are piñon/juniper woodlands, whereas red areas are primarily ponderosa pine forests. Flight lines where airborne imagery was collected are shown as yellow lines.

reflected in these maps and some obvious fine-scale errors were also present. Therefore, a three-class vegetation map (piñon/juniper, ponderosa pine and other conifers, and meadow/bare ground/other) was developed for the study area using image segmentation and regression tree classification (Figure 4) (Hamilton and others 2004). This map formed the PSUs. For this study, the entire 332,000-acre piñon/juniper cover type was advanced to the second stage of the sample.

**Stage 2—Percent-Cover Strata (SSUs)—**
Negron and Wilson (2003) reported that the likelihood of piñon ips infestation increased with stand density in Arizona. To reduce sample variance, this known source of variability was incorporated into the sample design by stratifying the piñon/juniper vegetation class by percent cover. The percent-cover strata became the SSUs. Breaks for the percent-cover strata were based on the broad-level vegetation cover categories established by the USDA Forest Service Existing Vegetation Classification and Mapping

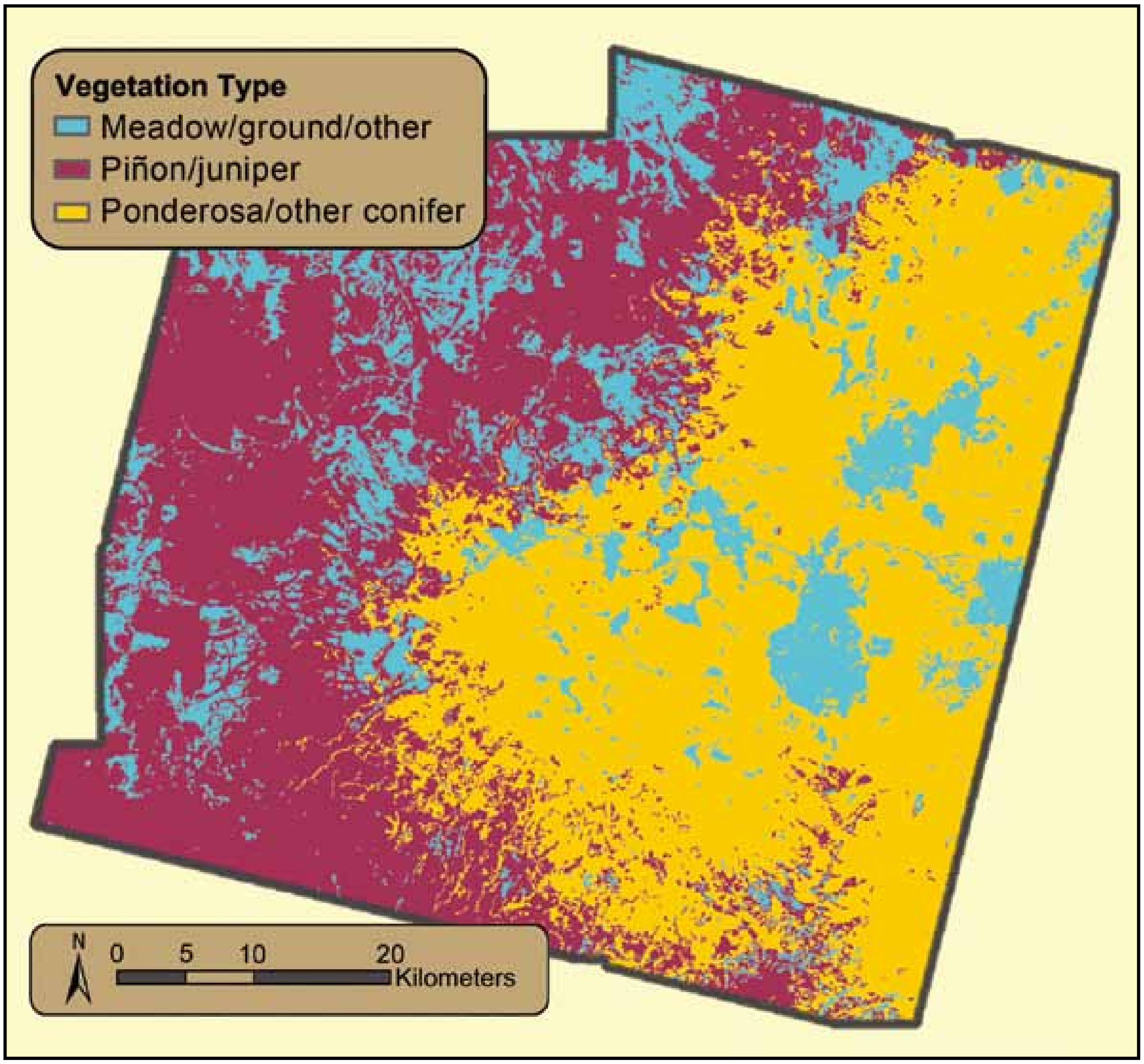


Figure 4—A vegetation-cover map, used to restrict the multistage sample to piñon/juniper woodlands, was created using regression tree classification. This is the first stage of the multistage sample.

Technical Guide (Brohman and Bryant 2005) (Table 1). The first vegetation-cover category (0 to 29.9 percent), was further subdivided into 0 to 9.9-percent and 10 to 29.9-percent categories to refine the SSUs.

Because no existing percent-cover maps were available for the study area, a map was created from 1992 digital orthophoto quadrangles (DOQs). The DOQs were not current, and we anticipated that the mapped percent cover would generally be lower than the actual percent cover. However, as the objective of this exercise was to stratify the study area (not to measure percent cover), relative differences in actual percent cover compared to mapped percent cover would still allow the map to serve its purpose of stratifying the study area. The relative differences in percent cover are inconsequential so long as percent cover and, consequently, mortality, is more homogeneous within than between strata. To create the percent-cover map, a two-class classification (tree and nontree) was created from the DOQs in ERDAS Imagine. Then, for each image segmentation polygon (average size ≈ 2.5 acre) used in the vegetation classification, the percentage of the polygon occupied by mapped trees was calculated (Figure 5). No accuracy assessment was conducted for the percent-cover map. However, final sample results verified that percent

**Table 1—Percent-cover ranges of SSU strata and strata acreages within the entire piñon/juniper region and the region of aerial imagery coverage are shown, including proportions by stratum of total study area and aerial imagery coverage for the two regions**

| Strata | Acreage and (proportion of total area) | |
|---|---|---|
| (percent-cover ranges) | Piñon/juniper region | Aerial imagery coverage |
| 0-9.9 percent | 36,224 (0.11) | 739 (0.10) |
| 10-29.9 percent | 108,633 (0.33) | 2,376 (0.32) |
| 30-59.9 percent | 140,162 (0.43) | 3,582 (0.49) |
| 60-100 percent | 39,430 (0.12) | 642 (0.09) |
| Total | 324,449 | 7,339 |

SSU = Secondary Sampling Units.

cover and mortality were more homogeneous within than between strata.

**Stage 3—Digital Aerial Imagery Plots (TSUs)—** Tertiary sampling units for this study consisted of 60-by 60-m digital aerial imagery plots. Plots were sampled for mortality using a digital dot grid. On March 30 and April 24, 2004, high-resolution digital camera (Kodak Pro Back 645C digital back attached to a Contax 645 medium format camera) imagery was acquired in 18 flight lines at various locations across the study area (Figure 3). The imagery was acquired with an 80 mm lens at an altitude of approximately 1375 m, producing 16-cm spatial-resolution imagery with a swath width of approximately 640 m. The imagery was orthorectified using OrthoBASE in ERDAS Imagine. Thirty TSU plots were randomly located within each percent-cover stratum (for a total of 120 plots) and the geographic boundaries of the aerial imagery. Although the percent-cover strata were not equal in size (Table 1), they were sampled equally to ensure a minimum number of samples in each stratum.

The plot size and dot density were chosen to optimize the accuracy and precision of the sample while minimizing the total number of dots per sample (i.e., minimizing costs). This was accomplished by sampling several areas from each percent-cover stratum using multiple dot grids, ranging in size from 30 by 30 m to 240 by 240 m with dot densities of 364, 648, or 1,012 dots per acre. A plot size of 60 by 60 m with dot density of 364 dots per acre (18 by 18 dots per plot) was considered optimal as the precision of the estimate increased only slightly with increased plot size or dot density or both. The dot grid was created from graphic elements in ArcGIS 8.3, allowing it to be moved easily from one plot to the next by dragging and dropping. Although this graphic dot grid worked well for this study, a new tool for ArcGIS 8.3 and 9.x, Digital Mylar—Image Sampler, was recently developed by the USDA Forest Service Remote Sensing Applications Center and now provides a more automated and user-friendly approach to dot grid sampling (USDA Forest Service 2005).

At each sample location, the dot grid was placed over the high-resolution imagery (Figure 6). The total number of dead-tree, live-tree, and ground hits from the dots was counted. First-year and later mortality were all grouped into the dead-tree category for this study. In this sampling procedure, piñon pines were not distinguished from junipers owing to the difficulty of distinguishing the two species on this imagery by photo interpretation. The proportion of each plot covered by dead trees, live trees, total tree cover (i.e., live plus dead trees), and other (typically bare ground) was calculated from the dot grids by tallying the hits of the individual variables and dividing by the total number of dots in the sample. Subsequently, mean values of these variables were calculated for each percent-cover stratum. The mean proportion of the entire piñon/juniper region (i.e., across all strata) covered by dead trees, live trees, total tree cover, and other was calculated from the estimates of each percent-cover stratum. These estimates were made using a standard weighted disproportionate-strata estimation equation, with the strata areas from Table 1 as weights (Equation 1) (Scheaffer and others 1990). Because relative proportions of strata areas for the entire piñon/juniper region were similar to those falling within the boundaries of the aerial imagery (Table 1), no adjustments were needed to extrapolate the estimate from the extent of the aerial imagery to the entire study area.

$$\hat{p}_{st} = \frac{1}{N} \sum_{i} (N_i \hat{p}_i) , \tag{1}$$

where $\hat{p}_{st}$ is the mean across-strata proportion of land area covered by dead trees, live trees, total tree cover, or other;

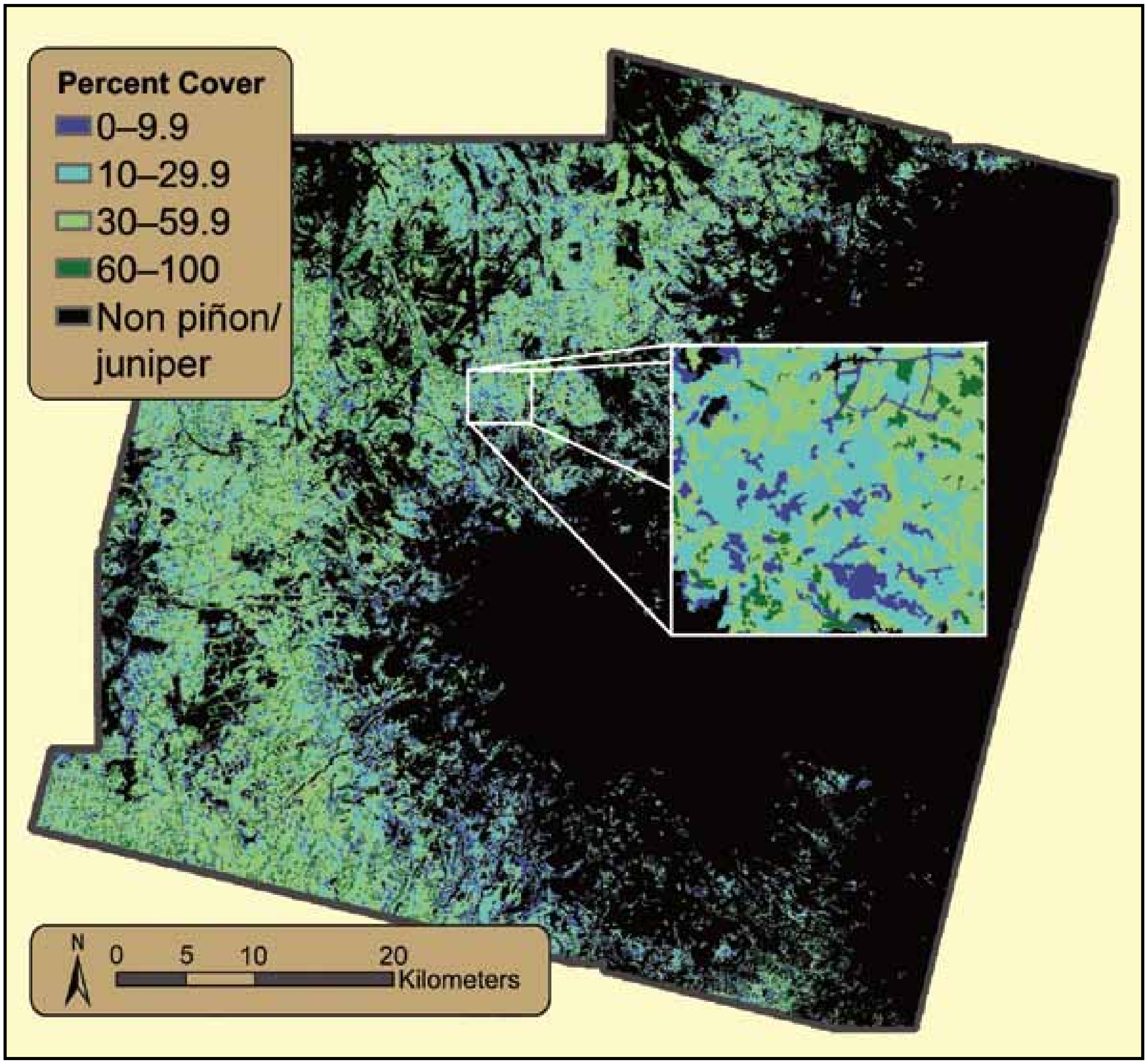


Figure 5—Percent-cover strata for the study area, derived from digital orthophoto quadrangles, were developed for the second stage of the multistage sample and formed the secondary sampling units.

$\hat{p}_i$ is the mean proportion of land area within each percent-cover stratum, indexed by *i*, covered by dead trees, live trees, total tree cover, or other; *N* is the total possible number of individual dot samples within the entire study area; and $N_i$ is the weight of the $i^{th}$ percent-cover stratum (i.e., the proportion of possible dot samples within the piñon/juniper forests of the $i^{th}$ percent-cover stratum to the total possible number of dot samples within the entire piñon/juniper forested area).

Standard errors of the across-strata mean proportion estimates were also calculated (Equation 2). From these results, the mean proportions of total tree cover that had died were calculated for each percent-cover stratum as well as across strata for the entire piñon/juniper population.

$$\hat{E}(\hat{p}_{st}) = 2\sqrt{\frac{1}{N^2}\sum_{i}^{n} N_i^{\,2}\left[\left(\frac{N_i - n_i}{N_i}\right)\left(\frac{\hat{p}_i\,(1-\hat{p}_i)}{n_i - 1,}\right)\right]} \qquad (2)$$

where $\hat{E}(\hat{p}_{st})$ is the error of the mean across strata proportion of land area covered by dead trees, live trees, total tree cover, or other; $n_i$ is the number of dot samples taken from each percent-cover stratum; and $N_i$, $N$, $\hat{p}_i$ are as described in equation 1.

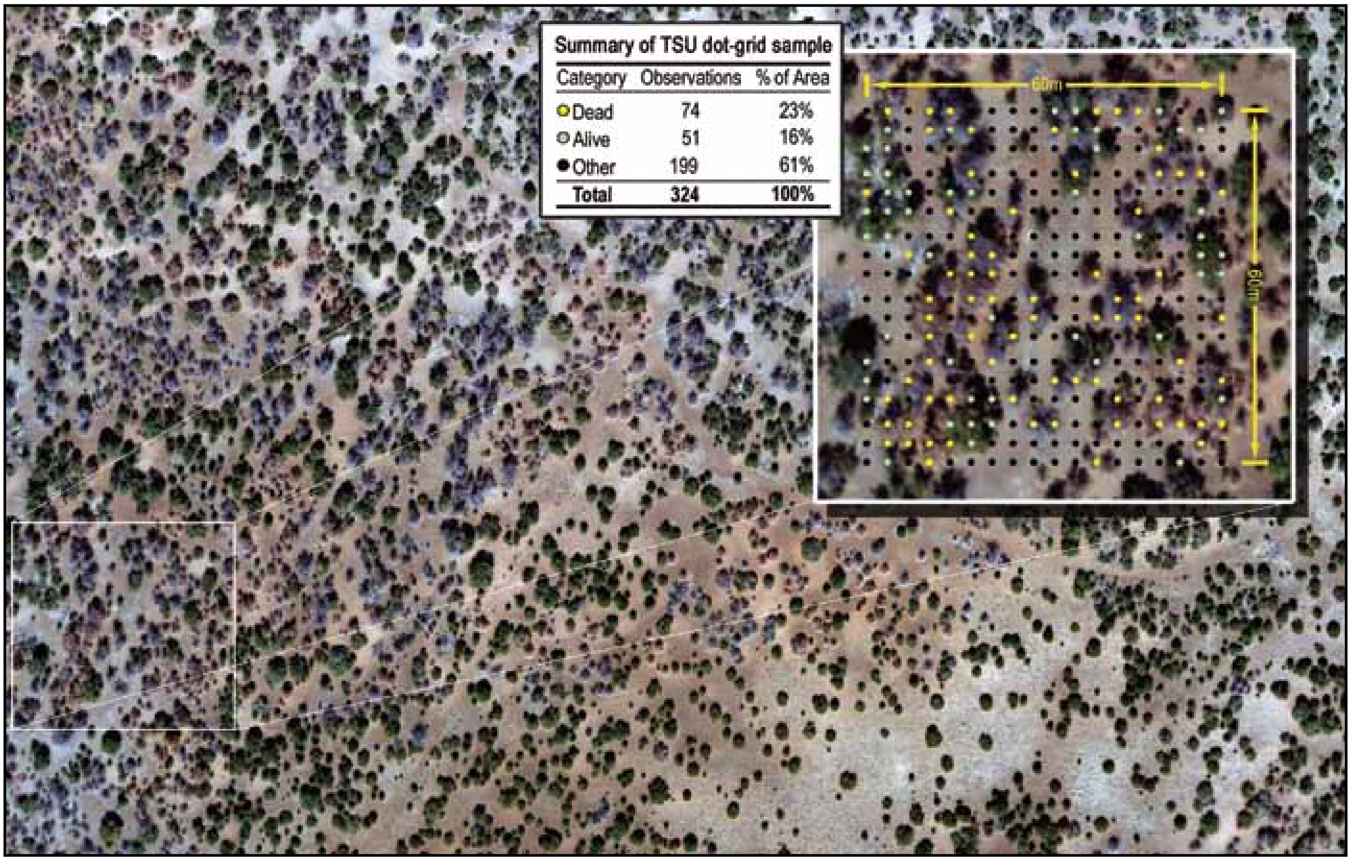


Figure 6—Natural-color, digital aerial imagery with dot-grid sample collected March 30, 2004, over an area of piñon mortality. The inset shows an example of a dot-grid sample of mortality within a 60 by 60 m (approximately 1 acre) tertiary sampling unit (TSU). Observations of dead trees, live trees, and other are color-coded and tallied for the site.

## Results and Discussion

Estimates calculated for the entire piñon/juniper region of the study area (across strata) showed that dead tree canopies occupied 7 ± 0.3 percent of the total area as viewed from aerial imagery (Table 2). As a percentage of total tree cover, 20 ± 0.8-percent mortality had occurred (Table 3).

Actual percentage of cover derived from the dot-grid samples often differed from the predefined percent-cover ranges of the SSUs. However, the stratification still served its purpose of reducing sample variance—percent cover and mortality were more homogeneous within than between strata. The results of this study generally support Negron and Wilson's (2003) conclusion that mortality increases with percent cover (Table 3).

Costs to conduct this multistage sample included $5,050 for materials and approximately 30 days of labor (Table 4). If labor were priced at $300 per day, the cost per acre for the 332,000-acre study area would be slightly more than $0.04. These cost estimates do not include the cost of creating a vegetation-cover map to narrow the study region to only piñon/juniper woodlands. It is assumed that sufficiently accurate digital maps of vegetation cover are or will soon be available for most of the Nation.

The cost incurred in this study can serve as a reference point for similar studies in other areas. However, costs can vary greatly depending on location, imagery resolution, size of the study area, and other factors. The cost-per-unit area, for example, is scale dependent—decreasing as the size of the study area increases.

## Conclusions

Forests and rangelands throughout the United States are at risk of severe insect and disease outbreaks and catastrophic wildfires. Epidemic insect infestations have already caused

**Table 2—Mean proportions of land area comprised of various cover types for each stratum. For each stratum, the mean proportions (±SE) of area (as viewed from aerial imagery) comprised of dead, live, and total tree cover, and ground are shown[a]**

| Stratum (percent-cover range) | Mean proportion of stratum land area, by type of cover | | | |
|---|---|---|---|---|
| | Dead | Live | Total tree cover | Ground |
| 0-9.9 | 0.021 ± 0.006 | 0.150 ± 0.018 | 0.171 ± 0.020 | 0.829 ± 0.020 |
| 10-29.9 | 0.059 ± 0.015 | 0.256 ± 0.014 | 0.315 ± 0.018 | 0.685 ± 0.018 |
| 30-59.9 | 0.090 ± 0.016 | 0.319 ± 0.018 | 0.409 ± 0.016 | 0.591 ± 0.016 |
| 60-100 | 0.082 ± 0.017 | 0.336 ± 0.021 | 0.418 ± 0.018 | 0.582 ± 0.018 |
| All strata | 0.071 ± 0.003 | 0.281 ± 0.005 | 0.352 ± 0.006 | 0.648 ± 0.006 |

[a] Weighted mean proportions (±SE) for the entire piñon/juniper study area (i.e., across strata) are also provided.

**Table 3—For each percent-cover stratum, the mean proportion (±SE) of total tree cover that has died, and mean weighted proportion (±SE) across all strata are provided**

| Stratum (percent-cover range) | Mean proportion of total tree cover that is dead |
|---|---|
| 0-9.9 | 0.125 ± 0.031 |
| 10-29.9 | 0.186 ± 0.033 |
| 30-59.9 | 0.221 ± 0.033 |
| 60-100 | 0.197 ± 0.033 |
| All strata | 0.196 ± 0.008 |

**Table 4—Approximate material costs and labor for an experienced analyst to conduct a multistage sample to estimate piñon mortality in the Williams Ranger District**

| Expense item | Labor (days) | Cost |
|---|---|---|
| Materials | | $5,050 |
| Orthorectification of aerial imagery | 9 | |
| Percent-cover stratification | 9.5 | |
| Dot-grid sampling | 10.5 | |
| Calculating results | 1 | |
| Total | 30 | $5,050 |

extensive mortality in many of the Nation's forests and rangelands. The severity and large extent of mortality, coupled with the lack of routine monitoring in some areas, has made it difficult to assess the damage, ecological impact, and fire hazard in a timely and cost-effective manner.

The multistage sampling method used in this study offers a statistically rigorous approach to estimate tree mortality across large geographic areas, increase sampling efficiency, and provide a confidence interval about the mean. By using a digital dot-grid to assess mortality from high-resolution aerial imagery, the need for time consuming and costly field assessments was eliminated. The use of imagery also allowed samples to be drawn from remote areas that would have been prohibitively time consuming to sample in the field. This method was tested over a 332,000-acre piñon/juniper woodland west of Flagstaff, Arizona, but the technique is applicable to many other forest types impacted by insects and diseases. The multistage sample estimated that, as of spring 2004, dead-tree canopies occupied approximately 7 percent of the area within the piñon/juniper woodlands of the Williams Ranger District. Relative to the total tree cover, approximately 20-percent mortality was sustained. For the piñon/juniper study area, the cost to estimate mortality was approximately $0.04 per acre. In other areas, the cost per unit area to conduct a similar study could vary greatly depending on the location, size of the study area, and imagery requirements.

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