Analysis of Conifer Mortality in Colorado Using Forest Inventory and Analysis's Annual Forest Inventory

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ABSTRACT

Aerial detection surveys indicate that widespread conifer mortality has been steadily increasing in Colorado, particularly since 2002. The Forest Inventory and Analysis (FIA) annual inventory system began in Colorado in 2002, which coincided with the onset of elevated conifer mortality rates. The current mortality event coupled with collection of 6 years of annual inventory data provided an opportunity to test the usefulness of the FIA annual inventory system for quantifying rapid change in the conifer resource over a large geographic area. The estimate of conifer mortality during the 2002–2007 period indicated an average of 44 million trees that died each year, which represents more than twice the average recorded in the 1997–2002 period. The estimate of insect-killed lodgepole pine averaged 10.5 million trees during the 2002–2007 period, which represents a 10-fold increase compared with the estimate recorded for the 1997–2002 mortality period.

Keywords: forest inventory, FIA, conifer, mortality, bark beetles

The Forest Inventory and Analysis (FIA) program is a national US Forest Service program that conducts forest inventory across all land ownerships in the United States. FIA inventories are based on a systematic sample, establishing permanent sample plots on the ground at an intensity of approximately one plot per 6,000 ac across the landscape. In the past, FIA conducted periodic inventories in which all plots in a given state were measured over a period of 1 or more years. Anywhere from 10 to 20 years might elapse between full periodic inventories of a particular state.

In the mid-1990s, the FIA program migrated from the periodic system to an annual inventory system (Gillespie 1999). The existing FIA plot grid was modified with the change from periodic to annual. A new systematic grid made up of 6,000-ac hexagons was superimposed over the United States, and one plot was randomly located within each hexagon. Existing FIA plots were retained when possible, but plots were added or deleted to achieve a sampling intensity of one plot per hexagon. The goal was to standardize the base plot network nationally while retaining as many existing plots as possible to preserve trend data. The hexagons were then systematically divided into panels, such that each panel had complete spatial coverage across the landscape, and the numbers of hexagons (plots) in each panel was approximately the same (Reams and Van Deusen 1999). In the western United States, one panel represents approximately one-tenth of all plots in a state, with the objective being that all plots will be measured in 10 years. The advantage of the annual inventory system is that data are available every year, which provides researchers with more timely data across the landscape. This system results in data being collected and compiled every year, which allows for more flexible analysis options and provides opportunities to monitor forest change in ways that were not possible using periodic inventory data.

The Interior West FIA (IW-FIA) program operates in Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, and Wyoming. The annual inventory system was implemented in Utah in 2000 and in most of the other IW-FIA states since then. The annual inventory began in Colorado in 2002, and as of 2007, six panels have been completed in that state.

Extensive and widespread conifer mortality occurred in Colorado during this interval. Most of this tree mortality is attributed to forest insects such as bark beetles and defoliators. The US Forest Service, Forest Health Management, has been conducting aerial detection surveys since 1997 to quantify tree mortality from drought, insects, and disease (US Forest Service 2001a, 2002, 2004, 2005). These extensive insect outbreaks have a significant visual impact and raise concerns about the sustainability of Colorado's forests and forest manager's ability to deal with these issues.

Drought-related stress is considered to be a contributing factor of some insect outbreaks (Logan et al. 2003, Carroll et al. 2004, Breshears et al. 2005). There have been outbreaks of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) in areas with a microclimate that were previously too cold and unusually large and intense mountain pine beetle outbreaks in high elevation pines (Logan and Powell 2005). Widespread mortality has been observed in the ponderosa pine and pinyon-juniper types in the Southwest. In IW states, where annual inventories have been implemented, this widespread and locally severe mortality has been geographically and temporally assessed by the FIA program (Shaw et al. 2005). Based on these assessments, the annual inventory approach has shown promise in detecting trend and magnitude of short-term change

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during a widespread event such as drought-related mortality (Shaw 2004).

The current mortality episode in Colorado has provided an opportunity to test the usefulness of the FIA annual inventory system for quantifying rapid change in mortality of the state's major conifer species. Here, I describe the advantages and potential limitations of assessing tree mortality using the annual inventory system, present the extent and severity of the conifer mortality event using the annual inventory system, and present statistical tests of the data that assist in validating the estimates.

Table 1. Number of inventory plots that sampled forestland in Colorado by mortality period, measurement year, and panel number.

Measurement year	Mortality period	Panel no.	No. of plots
2002	1997–2002	1	348
2003	1998–2003	2	358
2004	1999–2004	3	386
2005	2000–2005	4	389
2006	2001–2006	5	373
2007	2002–2007	6	379

Methods

Analysis Options

As previously mentioned, there are more analysis options for monitoring forest change under the annual inventory system than the periodic inventory system. One option is to simply compile the data as if it were a periodic inventory, ignoring the fact that some panels are several years older when compared with previous periodic inventories. This may be referred to as the moving average (Reams and Van Deusen 1999). A top priority for the FIA program is to provide standard inventory estimates every 5 years using this inventory option. The moving average is the procedure used to compile and store the annual inventory data in the national FIA database. However, a single periodic inventory makes trend analysis impossible. Mortality rates for a single periodic inventory may overestimate or underestimate a true baseline rate by either including or not including a significant short-term disturbance such as catastrophic fire or insect outbreaks. Furthermore, periodic inventory data are accurate for several years but become increasingly unreliable there after.

Another analysis option considers the fact that the annual inventory is an interpenetrating design. This may be referred to as the independent panel option. Under this approach, each annual panel is analyzed independently and estimates are produced on a yearly basis. The independent panel option is a design where the n units (FIA sample plots) are divided into $k = 10$ panels, each panel containing $m = n/k$ units. Panel 1 plots are measured in year 1, panel 2 plots are measured in year 2, and so on, such that all plots have been visited by the end of year 10. The panel cycle is repeated into perpetuity (Reams and Van Deusen 1999).

The advantage of the independent panel option is that trends in inventory estimates such as tree growth and mortality, natural disturbances, and human-induced changes such as forest harvesting can be assessed almost immediately. The independent panel option does have certain limitations. Because each panel represents only about one-tenth of all plots in Colorado, the smaller number of plots results in a higher variance around the individual panel estimate. Mortality estimates, in particular, are subject to high variance because tree mortality is relatively infrequent. Tree mortality does not always occur on every plot. For situations such as insect and disease outbreaks where mortality may be spatially spotty, the signature of the event may not be adequately captured with a limited sample size. Caution must also be exercised when screening data for single panels by certain attributes such as forest type or analyzing data for very small domains because the small number of plots may result in an unacceptably high variance. Variance reduction usually can be attained by combining current data with earlier data from previous panels (Patterson and Reams 2005). The technique used for combining panels depends on the different spatial, temporal, and forest characteristics within a region. Combining panels may also produce bias depending on which panels are grouped and the rate of change over time.

The last periodic inventory in Colorado was completed in 1983. Because of significant changes in inventory procedures that have occurred since 1983, estimates from the previous inventory are not considered comparable with current inventory estimates. Therefore, the only procedure for assessing short-term trends in conifer mortality trends in Colorado is the independent panel option where individual inventory panels corresponding to years can be compared against each other. All the conifer mortality analyses in this article will be from the independent panel option.

Sampling Design and Estimation Procedures

The plot design used in the annual inventory of Colorado is described in Bechtold and Patterson (2005). For this analysis, population estimates of tree mortality in Colorado were calculated for the individual panels with each panel number corresponding to a single measurement year (Table 1). The population estimate of numbers of conifer mortality trees was computed for each individual panel by compiling the data using only those plots measured in that panel. The population, in this analysis, is the total forest area in Colorado. The computational procedures used to estimate the average annual number of conifer trees that died on forestland in Colorado is described by US Forest Service (2001b). For each FIA plot that sampled forestland, the number of mortality trees per acre was calculated. This was done by summing the number of mortality trees measured on each plot and then dividing by the observed forest area on the plot, yielding an estimate of the number of mortality trees on a per-unit-area basis (Bechtold and Patterson 2005). The number and mean number of mortality trees per acre were the variables tested in the statistical analysis.

Estimating Tree Mortality

The IW-FIA program defines a mortality tree as one determined to have died within 5 years of the plot measurement date (US Forest Service 2007). Therefore, field crews make a distinction between trees that have recently died and long-standing dead trees on all plots that sample forestland. For this analysis, population estimates of the number of all mortality trees with a minimum dbh of 5.0 in. that qualify as mortality on forestland are used in this analysis. For multistemmed woodland species, the minimum size was determined by a diameter at root collar measurement of 5.0 in. Only trees that died due to natural causes were considered mortality trees; trees removed due to man-caused cultural activity (timber harvesting, timber stand improvement, land clearing, and more) were not included in the mortality estimate. All mortality trees are assigned a cause of death code by field crews. The causes of death assigned to mortality trees

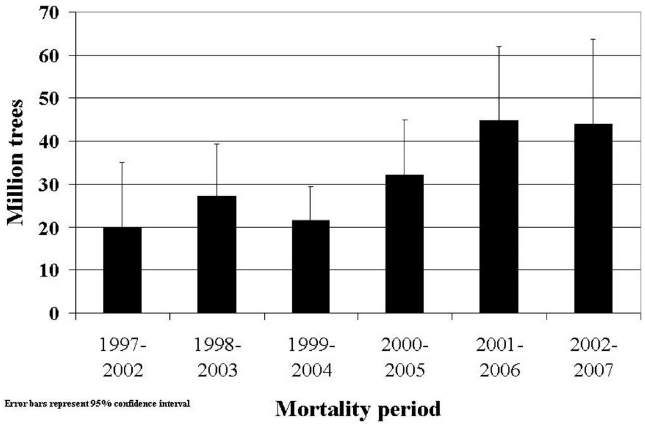

Figure 1. Average annual number of mortality conifer trees by mortality period in Colorado.

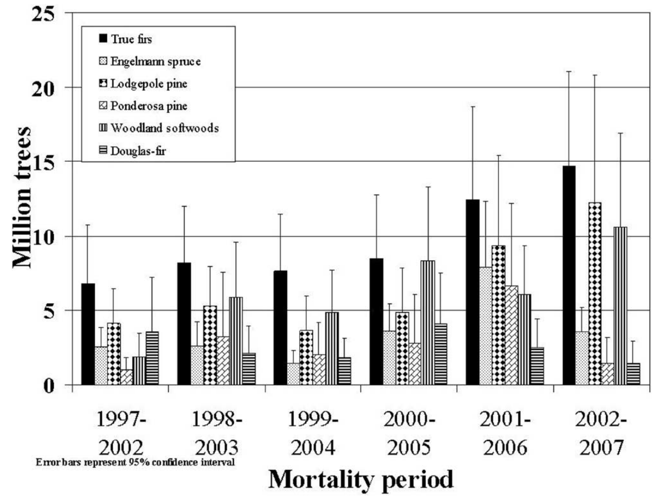

Figure 2. Average annual number of mortality conifer trees by conifer species group and mortality period in Colorado.

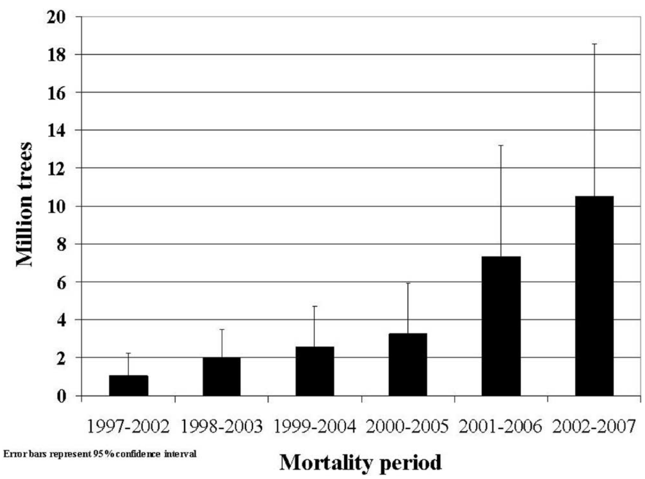

Figure 3. Average annual number of mortality lodgepole pines killed by insects by mortality period in Colorado.

in this analysis include insects, disease, fire, animal, weather, vegetation suppression, and unknown.

The average annual number of mortality trees is the population estimate of number of mortality trees averaged over a 5-year period. Therefore, the mortality estimates are actually averages that best represent the midpoint of the 5-year interval. For example, the mortality tree estimate for the year 2002 represents the average number of trees that died each year during the period 1998–2002. This period is termed mortality period in this article (Table 1). The reason behind this one-point-in-time mortality estimation procedure in Colorado is that the inventory data are limited to initial plot measurements. Complete remeasurement data for the state, where the status of the plot and all trees on the plot are known at two points in time, will not be available in Colorado until all 10 panels of data are completed and remeasurement begins in the 11th year.

Six conifer species or species groups were used in this mortality analysis for Colorado: (1) Douglas-fir (*Pseudotsuga menziesii*); (2) ponderosa pine (*Pinus ponderosa*); (3) true firs—subalpine fir (*Abies lasiocarpa*), white fir (*Abies concolor*), and corkbark fir (*A. lasiocarpa* var. *arizonica*); (4) Engelmann spruce (*Picea engelmannii*); (5) Lodgepole pine (*Pinus contorta*); and (6) Western woodland softwoods—twoneedle pinyon pine (*Pinus edulis* Engelm.), Utah juniper (*Juniperus osteosperma*), Rocky Mountain juniper (*Juniperus scopulorum*), and oneseed juniper (*Juniperus monosperma*).

Results

When all conifer species and species groups are combined, the annual inventory indicated higher levels of mortality in the latest two mortality periods compared with the four earlier periods (Figure 1). The estimate of conifer mortality during the 2002–2007 period indicated an average of 44 million trees that died each year, which represents more than twice the average of 20 million mortality trees recorded in the 1997–2002 period.

It is more informative to examine similarities and differences by conifer species and species groups (Figure 2). The highest level of mortality occurred in the true fir species group. The average annual number of true fir mortality trees was nearly 15 million trees in the 2002–2007 period compared with 6.8 million trees in the 1997–2002 period. Mortality of lodgepole pine also indicated an upward trend over the annual inventory time span. The average annual number of lodgepole pine mortality trees increased from 4.1 million trees during the 1997–2002 period to an average of 12.1 million trees during the 2002–2007 period. A dramatic increase in mortality over the annual inventory time span occurred in the woodland softwood species group. The number of woodland softwood trees that died during the 2002–2007 period averaged over 10 million trees/year, which represented a nearly sixfold increase compared with the 1997–2002 period.

Colorado is experiencing one of the largest outbreaks of mountain pine beetle in lodgepole pine forests since records became available for the state. As explained in the section "Estimating Tree Mortality" all trees that qualify as mortality on FIA plots are assigned a cause of death code that estimates the primary agent that caused the tree's death. Therefore, mortality estimates can be filtered on general cause of death codes such as insects, disease, and fire. Figure 3 illustrates the average annual numbers of lodgepole pines killed by insects. The assumption is that most of this insect-caused mortality of this species is caused by mountain pine beetle. The estimate of insect-killed lodgepole pine averaged 10.5 million trees for the 2002–2007 mortality period, which represents a 10-fold increase compared with the estimate recorded for the 1997–2002 mortality period.

Table 2. Bonferroni (Dunn) *t*-test of all combinations of individual mortality period estimates of mean number of mortality trees per acre by conifer species groups that had significant overall mortality period effect in Colorado.

Mortality period comparison	All conifers	Engelmann spruce	Lodgepole pine killed by insects
2002–2007/2001–2006			
2002–2007/2000–2005			
2002–2007/1999–2004	***		
2002–2007/1998–2003			***
2002–2007/1997–2002	***		***
2001–2006/2000–2005			
2001–2006/1999–2004		***	
2001–2006/1998–2003		***	
2001–2006/1997–2002			
2000–2005/1999–2004			
2000–2005/1998–2003			
2000–2005/1997–2002			
1999–2004/1998–2003			
1999–2004/1997–2002			
1998–2003/1997–2002			

*** Significant at the 0.05 level.

Table 3. Regression statistics, where *y* = plot-level number of mortality trees per acre by species group and *x* = mortality period midpoint by species group in Colorado.

Species group	Slope of mortality period coefficient	Standard error	*P*
All conifers	0.22947	0.05707	<0.0001
True firs	0.05615	0.02775	0.0432
Engelmann spruce	0.02052	0.01256	0.1024
Lodgepole pine (all causes of death)	0.07809	0.03194	0.0146
Lodgepole pine (insect-killed trees only)	0.09536	0.02971	0.0013
Ponderosa pine	0.02906	0.02012	0.1488
Woodland softwoods	0.06205	0.02332	0.0078
Douglas fir	−0.01640	0.01377	0.2337

Statistical analysis of the mortality data was performed in a three-step process. First, an analysis of variance (ANOVA) test using the ANOVA procedure was used to test the mean number of mortality trees per acre for a significant overall mortality period effect (SAS Institute 2000). The effect of mortality period on the mean number of mortality trees per acre was tested separately for eight conifer species groups: (1) all conifers combined, (2) true firs, (3) Engelmann spruce, (4) lodgepole pine, (5) lodgepole pines killed by insects, (6) Douglas-fir, (7) woodland softwoods, and (8) ponderosa pine. Three conifer species groups were identified has having significant mortality period effect; all conifers combined ($F = 3.82$; $P = 0.0019$), Engelmann spruce ($F = 3.22$; $P = 0.0067$), and lodgepole pines killed by insects ($F = 2.90$; $P = 0.0130$). Second, all combinations of 13 mortality periods for the three conifer species groups identified as having significant mortality period effect were tested against each other using the Bonferroni correction factor for multiple tests. The variable tested was the mean number of mortality trees per acre. This was done to identify which combinations of mortality periods differed significantly from each other. Table 2 illustrates the results of these tests. Third, a regression was fit to the data where the dependent variable was the conifer mortality per acre calculated for each plot and the independent variable was the mortality period midpoint. The regression test was performed for each of the eight conifer species groups. This was done to check the slope of the mortality period midpoint coefficient to determine the rate of change and if the slope differs significantly from 0. Table 3 illustrates the results of these tests.

Discussion

The annualized FIA inventory (Gillespie 1999) was implemented under the assumption that trends in forest attributes such as area, tree volume, tree growth, and tree mortality could be assessed in a timelier manner than periodic inventories. Proponents of the annual inventory design acknowledged that the variance associated with individual panel estimates would be higher than periodic inventories but would remain constant over time. Periodic inventories, they argued, have smaller variances around the estimates at any one point in time but the variances increase as time between inventories elapses.

Examination of the average annual mortality of conifers over the six mortality periods in Colorado indicated an upward trend for all conifers combined and some of the species groups individually (Table 3). There was, as expected, a large amount of variation associated with the mortality estimates for a given mortality period. This is because of the relatively small number of plots in a single panel and the relatively rare nature of tree mortality. However, the ability to detect trends in a mortality event over a short period of time was never possible with periodic inventories. For example, consider two periodic inventories, one conducted in 2000 and one conducted in 2010 with a major insect epidemic occurring over a 2-year period midway between the two inventories. The temporal dynamic—the ability to use mortality data for causal predictions and correlations with other biotic factors—of the mortality episode would be lost if the 2010 periodic mortality estimate is simply averaged over the 10-year period.

Insect infestations, such as the mountain pine beetle epidemic in lodgepole pine forests, are believed to be driving much of the increase and intensity of conifer mortality in Colorado. The reasons behind the recent outbreaks have received considerable discussion. Most bark beetles prefer to invade trees that are in poor physiological condition (Rudinsky 1962). Temperature is known to influence insect outbreaks, especially species such as the mountain pine beetle (Amman 1973). Because of the recent interest in climate change, the effect of global warming is believed by some researchers to be a contributing factor in the severity of mountain pine beetle infestations (Logan et al. 2003). On the other hand, the interaction of drought, stand density, and global warming is believed to be the reason for the high pinyon pine mortality rates (Furniss and Carolin 1977). Compounding the discussion is the species of trees, the species of insect, and the forest's relationship with fire, all which vary tremendously throughout Colorado. Some researchers argue that the current insect outbreaks now taking place in Colorado are similar in intensity as previously documented outbreaks in the Rocky Mountains.

The most pronounced increase in average annual mortality over the six mortality periods occurred in the insect-killed lodgepole pine species group. This is undoubtedly the influence of the mountain pine beetle epidemic affecting lodgepole pine forests in Colorado. However, drawing conclusions from mortality estimates by cause of death agents should be done with caution for two reasons. First, the actual agent that caused a tree's death may be impossible to determine in the field. Second, interactions between insects and diseases are complex and make identification of damaging agents difficult. A number of bark beetles are associated with diseased or damaged trees. For example spruce beetle (*Dendroctonus rufipennis*) often attacks trees weakened by root disease (Schmid and Frye 1977), western balsam bark beetle (*Dryocoetes confuses*) also attacks trees weakened by root disease (Keen 1958), and piñon ips (*Ips confuses*) often develops in trees injured or uprooted as in land clearing for range improvement (Furniss and Carolin 1977). Even experts in entomology and pathology often have a very difficult time determining the primary causal agent in many cases. Is the presence of disease what attracts bark beetles in endemic conditions? For epidemics, are diseased trees a refuge for bark beetles, which then erupt when a drought, a blowdown, or a defoliation event facilitate an increase in populations that can then survive independently of diseases?

Conclusion

Can FIA annual inventories help answer some of the questions associated with the mortality phenomena in Colorado? Initial results of the annual inventory in Colorado appear promising but many more years of annual data are needed before signatures of mortality events can be evaluated with confidence. Perhaps the greatest benefit of the annual inventory system is providing consistent application of data collection on the ground over a period of many years that can be correlated with time-series data such as temperature and rainfall data. Currently, reliable data on the extent of previous insect outbreaks is sometimes difficult to come by. Aerial surveys have some limitations in quantifying tree mortality. It is clear that accurate, consistent, long-term monitoring procedures are needed for managers and researchers to study relationships between tree mortality and changing climate patterns. The power to detect significant effects related to mortality and other parameters of interest will increase substantially with estimates derived from the remeasured (paired) plots that will be available in the second measurement cycle of Colorado.

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