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Assessing the Impact of a Mountain Pine Beetle Infestation on Stand Structure of Lodgepole Pine Forests in Colorado Using the Forest Inventory and Analysis Annual Forest Inventory

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The Forest Inventory and Analysis (FIA) annual inventory system began in Colorado in 2002, which coincided with the onset of a major mountain pine beetle (*Dendroctonus ponderosae*) epidemic. The mortality event, coupled with 11 years of annual inventory data, provided an opportunity to assess the usefulness of the FIA annual inventory system for quantifying the effects of the beetle epidemic on the numbers and distribution of lodgepole pines (*Pinus contorta*) in Colorado before, during, and after the infestation. Mortality of lodgepole pine peaked around 2007, averaging 38 million trees annually. The structure of existing lodgepole pine forests underwent a significant change after the beetle epidemic. The proportion of large-diameter live lodgepole pines dropped from an average of 37% over the years spanning 2003–2005 period to an average of 25% over the years spanning 2010–2012.

Keywords: forest inventory, FIA, lodgepole pine, mortality, bark beetles

The Forest Inventory and Analysis (FIA) program is a national US Department of Agriculture (USDA) 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 acres 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-acre 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 for monitoring 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

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2002, and as of 2012, 11 panels have been completed in that state. Extensive and widespread conifer mortality occurred in Colorado during this interval (Thompson 2009). The most significant episode occurred in lodgepole pine (*Pinus contorta*) forests, where a mountain pine beetle (*Dendroctonus ponderosae*) infestation caused significant mortality of this species over extensive areas in Colorado. Results from the FIA inventory and aerial detection surveys conducted by the USDA Forest Service, Forest Health Management, indicate that the epidemic appeared to peak in the mid-2000s and has since tapered off.

The annual inventory has shown promise for detecting the trend and magnitude of short-term changes in widespread events such as drought-related mortality and insect epidemics (Shaw 2004, Thompson 2009). The purpose of this study is to apply the same analysis techniques to assess the beginning and end of the beetle epidemic by examining trends in lodgepole pine mortality and to assess the subsequent effect the mountain pine beetle epidemic had on the number and distribution of residual lodgepole pine trees in Colorado.

Impacts of Mountain Pine Beetle on Lodgepole Pine Forests

The reasons behind the recent mountain pine beetle impact in Colorado have received considerable discussion. Most bark beetles prefer to invade trees that are in poor physiological condition (Rudinsky 1962). This has led to speculation about the overall condition of Colorado's lodgepole pine forests. Temperature is known to influence bark beetle outbreaks (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). Compounding the discussion is lodgepole stand structure, species composition, and the relationship with fire, all of which vary tremendously throughout Colorado.

Several studies have quantified short-term impacts of mountain pine beetle (Amman and Baker 1972, Muir 1993, Sibold et al. 2007, Vyse et al. 2009). The purpose of some of these studies was to assess the effect of various treatments and management strategies in beetle-infested lodgepole pine stands (Amman and Baker 1972). Other studies have concentrated on quantifying the effect of the long-term hazard associated with high dead fuel loading after elevated mortality caused by a mountain pine beetle epidemic (Heinrichs 1983, Lotan et al. 1985, Schmid and Amman 1992).

There have also been studies that examined the forest composition after a mountain pine beetle epidemic. Studies of mountain pine beetle in lodgepole pine forests show that the beetle generally attacks large-diameter, overstory trees, although once an epidemic begins, smaller trees can also be killed (Amman and Cole 1983). In Colorado, studies indicate that the mountain pine beetle killed more than 70% of lodgepole stand basal area in many regions (Klutsch et al. 2009, Collins et al. 2010). Smaller lodgepole pines may grow and become dominant in a stand after the outbreak is over (Romme et al. 1986, Sibold et al. 2007, Klutsch et al. 2009). There are numerous theories on the effect of mountain pine beetle infestations on forest productivity. One such study found that some forest systems showed great resilience, and the effects of beetles on primary productivity do not appear to be as severe as conventional wisdom maintains (Amman and Cole 1983).

What most of these studies have in common is a methodology that concentrates on quantitative measurements in stands that have been affected to some degree by mountain pine beetles. The study areas were relatively small. But what is the impact of a mountain pine beetle infestation on lodgepole pine forests over a large geographic area such as the state of Colorado? Have the numbers and volume of lodgepole pines in forests covering Colorado been significantly reduced? Is the diameter distribution of lodgepole pines in Colorado sustainable after the infestation? These are the questions that can be answered by a broad-scale inventory with an unbiased plot network.

Methods

Analysis Options

As previously mentioned, there are more analysis options for monitoring forest change under the annual inventory system than under the periodic inventory system. One 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 distur-

Management and Policy Implications

The Interior West region has recently experienced large-scale mortality of several tree species, including commercially valuable forest species such as lodgepole pine. Much of the mortality is the result of epidemic-level infestations of insects such as mountain pine beetle. The immediate effect of these epidemics is visual impact and loss of commercially valuable tree volume. However, forest managers are becoming increasingly concerned about the long-term impacts on sustainability, structure, and composition of future western forests. This article examined the use of the Forest Inventory and Analysis (FIA) annual forest inventory system to explain some of the effects of these large-scale disturbances on the forest resource by comparing trends in lodgepole pine mortality with trends in the number of live lodgepole pines before, during, and after a mountain pine beetle epidemic in Colorado. A general premise of forest managers is that modern silviculture should be based, in large part, on natural disturbance patterns and species adaptations to these disturbances. An understanding of forest stand dynamics is therefore a prerequisite to sound forest management. This article provides an overview of how a mountain pine beetle epidemic affected stand structure in lodgepole pine forests in Colorado. One implication of this work for forest managers is a better understanding of how a forest structure is affected by a significant disturbance over a relatively short period of time. From a forest management perspective, this implies a way to design silvicultural treatments to create a desired stand structure. Another implication is that by a better understanding of how lodgepole pine forests respond to mountain pine beetle epidemics, forest managers can make projections of future conditions and design future forest developmental trajectories.

Table 1. Number of inventory plots that sampled forest land and number of plots with at least one lodgepole pine measured classified as mortality in Colorado by mortality period, measurement year, and panel number.

Measurement year	Mortality period	Panel no.	No. of plots that sampled forest land	No. of plots with at least one mortality lodgepole pine measured
2002	1997–2002	1	411	23
2003	1998–2003	2	446	25
2004	1999–2004	3	460	19
2005	2000–2005	4	447	20
2006	2001–2006	5	410	22
2007	2002–2007	6	409	31
2008	2003–2008	7	387	34
2009	2004–2009	8	415	37
2010	2005–2010	9	406	35
2011	2006–2011	10	400	34
2012*	2002–2012	11	365	41

* Beginning of annual-to-annual remeasurement.

bances, 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. Another consideration of mortality estimates is that FIA compiles and reports tree mortality as an annual average over a measurement interval. Therefore, a mortality estimate associated with a measurement year is best represented by the midpoint of the measurement interval. For example, a mortality estimate for the measurement year 2009 is best represented by the midpoint of the measurement interval 2004–2009, which would be the year 2006 or 2007 (Table 1).

Independent panel estimates of live tree attributes are somewhat simpler to interpret than change estimates such as growth and mortality. An estimate of the number of live trees or live-tree volume can be generated for a specific year using only those plots measured in that year. Unlike change estimates, a live inventory estimate for a specific year is not an average; it is a valid estimate of a population total for that year. Because of the abundance of live trees compared with that of mortality trees, the variance estimates are considerably lower, resulting in a higher level of statistical confidence.

Statistical Analysis

Statistical analysis of the lodgepole live and mortality data was performed in a two-step process. First, an analysis of variance procedure was used to test the mean per acre number per inventory plot of lodgepole pine mortality trees, lodgepole pine ingrowth trees, small-diameter live lodgepole pine trees, and large-diameter lodgepole pine trees for a significant overall measurement year effect (SAS Institute, Inc. 2000). Measurement year had a significant effect on number of large-diameter lodgepole pines ($F = 4.09$; $P < 0.0001$) and on number of lodgepole pine mortality trees ($F = 4.60$; $P < 0.0001$). No significant effect of measurement year was observed for number of ingrowth lodgepole pines ($F = 1.13$; $P = 0.3341$) or number of small-diameter lodgepole pines ($F = 1.16$; $P = 0.3161$).

Second, all combinations of 11 measurement years for the per acre number of large-diameter and mortality lodgepole pine identified as having a significant measurement year effect were tested against each other using the Bonferroni correction factor for multiple tests. This was done to identify which combinations of measurement years differed significantly from each other. Tables 2 and 3 illustrate these results.

Sampling Design and Estimation Methods

The plot design used in the annual inventory of Colorado is described in Bechtold and Patterson (2005). For this analysis, population estimates of live and dead lodgepole pines in Colorado were calculated for the individual panels with each panel number corresponding to a single measurement year (Table 1). The population in this analysis is the state of Colorado. The compilation of numbers of live and mortality lodgepole pines in Colorado for individual panels was done by an estimation tool, Forest Estimation and Analysis (Frescino et al. 2012). This is a research tool designed for analysts who work in the open-source, R statistical programming environment. It is a collection of R functions that can access FIA databases and summarize plot and spatial data for any number or combination of annual inventory panels. In addition to population-level summaries, the tool can also generate statistical estimates of reliability as described in Bechtold and Patterson (2005).

Table 2. Combinations of individual measurement year estimates of mean number of live large-diameter (at least 9.0 in. dbh) lodgepole pine trees per acre that had significant measurement year effect in Colorado using the Bonferroni (Dunn) *t*-test.

Measurement year	Significantly different measurement years
2002	2007, 2008, 2009, 2010, 2011, 2012
2003	2008, 2009, 2010, 2011, 2012
2004	2007, 2008, 2009, 2010, 2011, 2012

Significant at the 0.05 level.

Table 3. Combinations of individual measurement year estimates of mean number of mortality lodgepole pine trees per acre that had significant measurement year effect in Colorado using the Bonferroni (Dunn) *t*-test.

Measurement year	Significantly different measurement years
2002	2008, 2009, 2010, 2011, 2012
2003	2008, 2009, 2010, 2011, 2012
2004	2008, 2009, 2010, 2011, 2012
2005	2008, 2009, 2010, 2011, 2012
2006	2009
2007	2009

Significant at the 0.05 level.

Data

FIA data used in this analysis were screened to only include tree records where the species was lodgepole pine with a minimum diameter of 5.0 in. dbh in Colorado. The independent panel option was chosen where population estimates of live and mortality trees were generated for individual

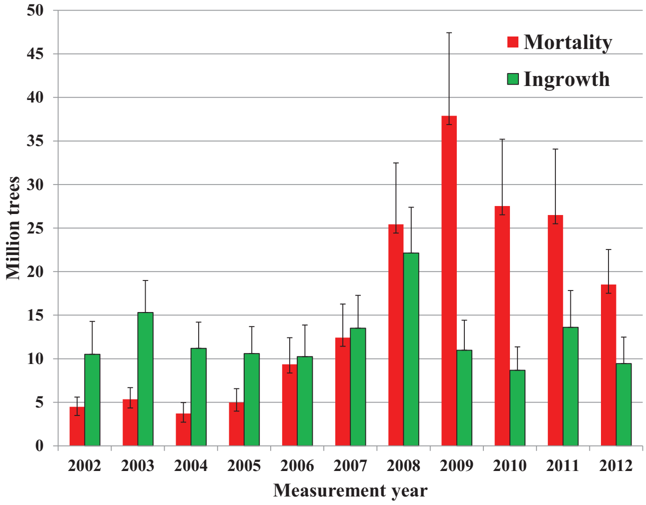

Figure 1. Comparison between average annual numbers of lodgepole pine mortality trees and numbers of ingrowth lodgepole pine trees by measurement year in Colorado. Error bars represent 95% confidence levels.

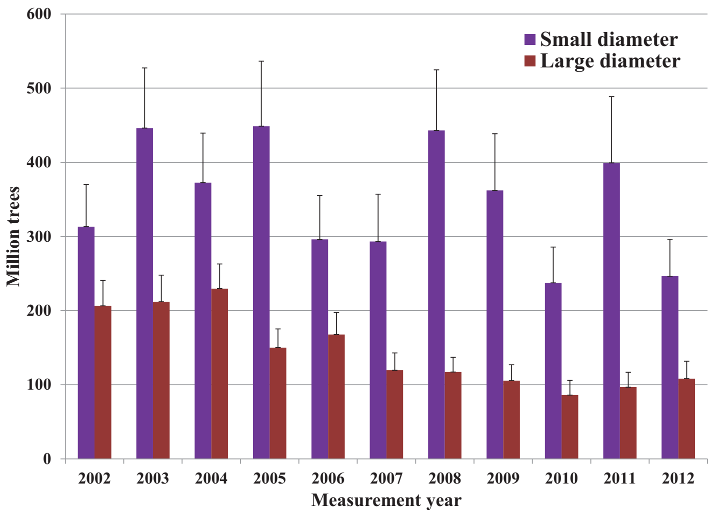

Figure 2. Numbers of live lodgepole pine trees 5.0 in. and larger by tree size class and measurement year in Colorado. Error bars represent 95% confidence levels.

panels. Three tree-level estimates were used in this inventory analysis of lodgepole pine: live trees, ingrowth, and mortality.

Live lodgepole pines were classified as alive and standing at the time of the plot visit. Trees classified as ingrowth are live trees that are estimated to have grown over the 5-in. dbh threshold for a given measurement year. Tree diameter growth for IW-FIA plots measured for the first time is estimated from increment core measurements. For remeasured plots, plots with a visit at two points in time where the status of all trees are known at both points in time, diameter growth is obtained from the measurement of diameters at time 1 and time 2. Based on these measurements, a live tree's diameter is projected or grown back in time for 1 year to obtain an initial diameter. Therefore, any live tree that has a current diameter of 5.0 in. dbh or larger and a projected initial diameter of less than 5.0 in. dbh is classified as ingrowth.

The IW-FIA program defines a mortality tree as one determined to have died within 5 years of the plot measurement date on plots visited for the first time (USDA Forest Service 2013). Table 1 illustrates the number of plots where at least one lodgepole pine was measured and classified as mortality. On remeasured plots, a tree is classified as mortality if the status at time 1 is alive and the status at time 2 is dead. The remeasurement interval between plot visits averages about 10 years in the Interior West region. This interval for new and remeasured plots is referred to as mortality period (Table 1). Only trees that died due to natural causes were considered mortality trees; trees removed due to man-caused cultural activity (e.g., timber harvesting, timber stand improvement, and land clearing) were not included in the mortality estimate. Population estimates of numbers of trees identified as lodgepole pines with a minimum dbh of 5.0 in. that qualify as mortality on forestland in Colorado are used in this analysis and are expressed as average annual number of trees that died during the mortality period.

There were 11 years, or panels, of data used in the study beginning in 2002 and ending in 2012. This 11-year period spans the beginning and end of the Colorado mountain pine beetle epidemic. Note in Table 1 that the mortality period in 2012 changes from 5 to about 10 years. The year 2012 marks the beginning of the remeasurement phase of Colorado's annual inventory where plots initially established in 2002 are revisited and remeasured in 2012.

Results

Figure 1 illustrates the relationship between the average annual number of lodgepole pine trees classified as mortality and the number of ingrowth lodgepole pines by measurement year in Colorado. Beginning in measurement year 2002, the annual number of lodgepole pine mortality trees averaged 4.5 million trees compared with 10.5 million live lodgepole pines entering the measurement year 2002 inventory estimates by growing over the 5-in. dbh threshold. During the measurement years 2002–2005, the number of lodgepole pine ingrowth trees was more than double the average number of mortality trees (Figure 1). In the measurement year 2006, believed to be the beginning of the epidemic, lodgepole mortality began to increase rapidly, peaking in the measurement year 2009 at an annual average of 38 million trees. This represents a more than 8-fold increase compared with the measurement year 2002 mortality estimate. After 2007, lodgepole mortality began to rapidly outpace the ingrowth estimate. With the exception of 2008, where lodgepole pine ingrowth jumped to 22 million trees, the estimates of ingrowth over the 11 panels were relatively stable with no significant upward or downward trends noted.

Figure 2 compares trends in the number of live lodgepole pines by measurement year for two tree size classes: small diameter (5.0–8.9 in. dbh) and large diameter (9.0 in. dbh and larger). Small-diameter lodgepole pines show fluctuation by measurement year but no significant trend over the 11 inventory panels. Numbers of large-diameter lodgepole pines do show a significant reduction over the time period. During the years 2003–2004, numbers of live large-diameter lodgepole pines averaged about 215 million trees in Colorado. After 2009, numbers of live large-diameter lodgepole pines averaged about 97 million trees.

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 more timely manner than periodic inventories. The premise behind the annual inventory design was that the variance associated with individual panel estimates would be higher than periodic inventories but would remain constant over time, thus allowing for timelier inventory estimates.

Examination of the relationship between lodgepole pine ingrowth and annual mortality by each measurement year illustrates the advantage of using broad-scale inventory data to better quantify the actual net loss of trees due to a disturbance event over time. In typical nonepidemic periods with normal baseline tree mortality, losses of trees dying of natural causes are generally offset by an equal amount of tree growth (Manion and Griffin 2001). Inventories of an abundant species over a large geographic area usually remain relatively stable over time. As Figure 1 illustrates, before the beetle epidemic, the number of new trees entering the inventory actually exceeded trees leaving the inventory due to mortality by a significant margin. Also noted is that, despite the dramatic increase in lodgepole pine mortality that peaked in 2009, the numbers of ingrowth trees remained at about the same level between 2002 and 2012.

The effect of the mountain pine beetle infestation on residual lodgepole pine stand structure was pronounced (Figure 2). The number of live large-diameter lodgepole pines trees essentially declined by more than 50% during the 11-year study period, whereas the number of small-diameter trees remained unchanged. The impact on stand structure resulted in an altered size class distribution of lodgepole pine forests in Colorado. During the years 2003–2005, the proportion of small-diameter trees averaged 63% of the total number of lodgepole pine trees at least 5.0 in. dbh in Colorado. During the years 2010–2012, that same proportion of small-diameter trees averaged 75%. Therefore, in a relatively short period of time, lodgepole pine forests shifted to younger stands comprised of smaller trees before the beetle infestation.

It is generally assumed that for a diameter class distribution to be stable, average growth rates and average mortality rates must be proportional across all diameter classes (Meyer and Stevenson 1943, Rubin 1999, Manion and Griffin 2001). The mountain pine beetle infestation had virtually no effect on the small-diameter trees. The large number of small-diameter trees relative to large-diameter trees coupled with the constant influx of ingrowth trees crossing over the 5.0-in. diameter threshold each year was enough to offset the losses due to mortality. The significant reduction of the large-diameter trees was due to the losses of beetle-caused mortality greatly outpacing new large-diameter trees entering the inventory. Obviously, if the high mortality rate that occurred in the measurement year 2009 were to continue for several more years, the effect on the number of large-diameter lodgepole pines would be catastrophic and unsustainable. What remains to be seen is how long it will take for enough small-diameter trees to populate the larger size classes to return lodgepole pine forests to the diameter distribution that existed prior to the epidemic.

Conclusion

This study illustrates how the FIA annual inventory may be used to assess forest resource attributes affected by disturbances such as insect infestations over a short period of time. Using annual inventory data to quantify the effects of disturbance events on forest attributes provides valuable information to forest managers interested in sustainability, structure, and composition of future forests. Unlike aerial surveys, inventory data collected and compiled on an annual basis can assess the immediate impact of disturbance regimes on forest community structure and organization. Another benefit of the annual inventory system is providing consistent application of data collection techniques that may be correlated with ancillary time series data such as temperature and rainfall statistics. Considering the recent concern over the impact of climate change on the severity and magnitude of forest disturbances, it is clear that accurate, consistent, long-term monitoring procedures are needed for researchers to study relationships between disturbance regimes and changing climate patterns.

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