Ecological Indicators 10 (2010) 713–718

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Comparing evaluations of forest health based on aerial surveys and field inventories: Oak forests in the Northern United States

C.W. Woodall [a,*], R.S. Morin [b], J.R. Steinman [c], C.H. Perry [a]

[a] USDA Forest Service, Northern Research Station, 1992 Folwell Avenue, St. Paul, MN 55108, USA
[b] USDA Forest Service, Northern Research Station, 11 Campus Blvd., Suite 200, Newtown Square, PA, USA
[c] USDA Forest Service, State and Private Forestry, 11 Campus Blvd., Suite 200, Newtown Square, PA, USA

ARTICLE INFO

Article history:
Received 9 February 2009
Received in revised form 22 November 2009
Accepted 27 November 2009

Keywords:
Oak forests
Forest health assessments
Forest inventory and analysis
Mortality
Aerial damage surveys

ABSTRACT

Aerial sketch-map surveys and systematic forest field inventories may be used separately or in combination to indicate the status of regional forest health. During recent decades, aerially conducted sketch-maps of forest damage and forest inventories have been used to assess oak (*Quercus* spp) forest health across a 24-state region spanning the northern U.S. In order to more fully inform the monitoring of oak forest health and integrate these independent datasets, the effect of the quality, timing, and repeated sampling of aerial data on correlations with field-based oak forest assessments was assessed. Study results indicated that aerial damage surveys were weakly correlated with indicators of oak forest sustainability (e.g., oak seedlings and saplings), but more highly correlated with overstory attributes such as tree mortality and standing dead. The highest correlations between aerial damage surveys and oak mortality/standing dead were found when the time between the aerial survey and subsequent forest inventory was 4–6 years. Aerial surveys may have their greatest efficacy in supplementing field inventories of oak forest health when they are conducted in a high quality manner with bi-annual or longer remeasurement periods (due to rare pest damage events).

Published by Elsevier Ltd.

1. Introduction

It has been proposed that North America's oak (*Quercus* spp.) forests may be entering an extended period of poor growth and susceptibility to invasive pests and droughts (Kessler, 1992), a situation that has been a national forest health problem since 1960 (Thomas and Boza, 1984). The deterioration of oak forest health, evidenced by numerous symptoms and precipitated by various causal factors, is collectively termed "oak decline" (Thomas and Boza, 1984; Starkey and Oak, 1989; Lawrence et al., 2002). Oak decline results from the interaction of predisposing stress factors (defoliating insects, drought, frost/ice damage, poor site quality, and advanced tree age) and secondary disease and insect pests (root fungi, canker fungi, and insect borers) (Starkey and Oak, 1989; Manion, 1991; Lawrence et al., 2002). This multitude of stresses eventually weakens oak trees resulting in sparse foliage, thin crowns, crown dieback, reduced radial growth, and eventually death (Lawrence et al., 2002). Silvicultural efforts to reduce tree mortality have included stand density reductions, increasing species diversity, removal of senescing oaks (Clatterbuck and Kauffman, 2006), and reducing vulnerability to gypsy moth impacts (Gottschalk, 1993). Because oak decline is a complex etiological combination of predisposing, inciting, and contributing factors (Manion, 1991; Oak et al., 1996), there is need for baseline data, long-term studies, and new analytical procedures (Kessler, 1989; Nebeker et al., 1992; Oak et al., 1996). The decline and mortality of oaks have been noted across its range in the northern US since the late 1970s and oak decline is one component of the broader issue of oak sustainability (for examples see Dwyer et al., 1995; Lawrence et al., 2002; Woodall et al., 2005, 2008; Widmann and McWilliams, 2007). Across the northern U.S. the growing stock volume of oak tree species on timberland has increased over 77% since 1963 to a present day total of over 1.4 billion cubic meters (Smith et al., 2004, 2008). However, other tree species commonly associated with oak forest types such as ash (*Fraxinus* spp.), maples (*Acer* spp.), and yellow-poplars (*Liriodendron tulipifera*) had net growing stock volumes increases of 251, 134, and 132% since 1963, respectively. Despite oak's prevalence across the northern U.S., evidence from recent studies (Shifley and Woodall, 2007; Widmann and McWilliams, 2007) suggests that both oak sapling mortality and a lack of seedlings portend a doubtful future for oak forests.

The science of monitoring forest health and sustainability (such as oak decline) is an emerging effort with numerous knowledge gaps, notably the synthesis of disparate sources of monitoring

* Corresponding author. Tel.: +1 651 649 5141; fax: +1 651 649 5140.
E-mail address: cwoodall@fs.fed.us (C.W. Woodall).

1470-160X/$ – see front matter. Published by Elsevier Ltd.
doi:10.1016/j.ecolind.2009.11.012

information (Hickey, 2008). The Forest Health Monitoring (FHM) Program of the U.S. Department of Agriculture's Forest Service (USFS) is responsible for monitoring the health of U.S. forests (Bechtold et al., 2007). The FHM program uses a three-tiered approach to monitoring health that consists of detection monitoring, evaluation monitoring, and intensive site monitoring. FHM's detection monitoring tier often consists of forest health experts delineating areas of declining forest health via aerial sketch-mapping. These aerial maps are often the first survey effort to detect emerging forest health threats followed by close monitoring by field-based sampling of forest health indicators. Regional assessments of oak forest health have often been monitored using such an approach of coupled aerial surveys and ground-based forest health indicator sampling (e.g., Steinman, 2004). Aerial and ground surveys of forest damage, in conjunction with systematic forest inventory plot data, offer the opportunity to assess the relationship of oak condition with damages associated with oak decline across the range of the genus in the northern United States. At least one past study integrated forest inventory data with aerial survey data in the Allegheny National Forest in Pennsylvania (Morin et al., 2004), but this method had never been utilized at the landscape level prior to Morin et al. (2009). Can aerial surveys (i.e., expert aerial sketch-mapping) be conducted in a more efficient and effective manner to supplement forest inventories for monitoring oak forests? Can this methodology be extended to indicate the current status of numerous other forest health issues (e.g., emerald ash borer, *Agrilus planipennis*)? Overall, can the purposive sampling nature of aerial surveys and damage detection be holistically combined with the systematic sampling nature of forest inventories to create better indicators of forest health?

The goal of this study was to compare aerial damage surveys and systematic field inventories of oak forests in the 24-state region of the northern U.S. with specific objectives including: (1) to determine correlations between oak forest attributes derived from field inventories (e.g., standing dead volume, seedling counts, live tree mortality) and aerial damage surveys, (2) to determine the effect of the quality and number/frequency of aerial surveys on correlations with oak forest attributes based on forest inventories, and (3) to suggest opportunities to improve the efficacy of aerial damage surveys in supplementing forest inventories when monitoring regional forest health issues using oak forests as a case study.

2. Methods

2.1. Forest inventory data

The Forest Inventory and Analysis (FIA) program of the USDA Forest Service, the only congressionally mandated national inventory of U.S. forests, conducts a 3-phase inventory of forest attributes of the country (Bechtold and Patterson, 2005). The FIA sampling design is based on a tessellation of the United States into hexagons approximately 2428 ha in size with at least one permanent plot established in each hexagon. In phase 1, the population of interest is stratified and plots are assigned to strata to increase the precision of estimates. In phase 2, tree and site attributes are measured for forested plots established in each hexagon. Phase 2 plots consist of four 7.32-m fixed-radius subplots on which standing trees are inventoried. For assessment of current oak forest attributes, inventory data from 1999 to 2006 were utilized with a total of 17,421 inventory plots included in the analysis. This study's 24-state study region includes: CT, DE, IL, IN, IA, KS, ME, MD, MA, MI, MN, MO, NE, NH, NJ, NY, ND, OH, PA, RI, SD, VT, WV, and WI (Fig. 1). Plots were included in the analysis if at least one oak tree greater than 2.54 cm diameter at breast height (DBH) was measured. Because growth/removals/mortality were not observed on all inventory plots, lower sample sizes occurred when these variables were utilized and are noted in results. For more details regarding FIA's forest inventory please refer to Bechtold and Patterson (2005) and USDA (2007).

2.2. Aerial damage surveys

The national FHM (Forest Health Monitoring) program was initiated by the USDA Forest Service in 1990 to monitor, assess, and report the status of and trends in forest health across the Nation (Bechtold et al., 2007). The survey component of FHM detection monitoring consists of aerial and ground surveys to detect damage in the form of tree defoliation, mortality, and damage as associated with the occurrence of damaging insects, diseases, windthrow, and other biotic and abiotic forest disturbances (Conkling et al., 2005). Aerial sketch-map surveys supply a landscape-level overview of forest health conditions at a relatively low cost (McConnell et al., 2000; Johnson and Ross, 2008; Johnson and Wittwer, 2008). Forest

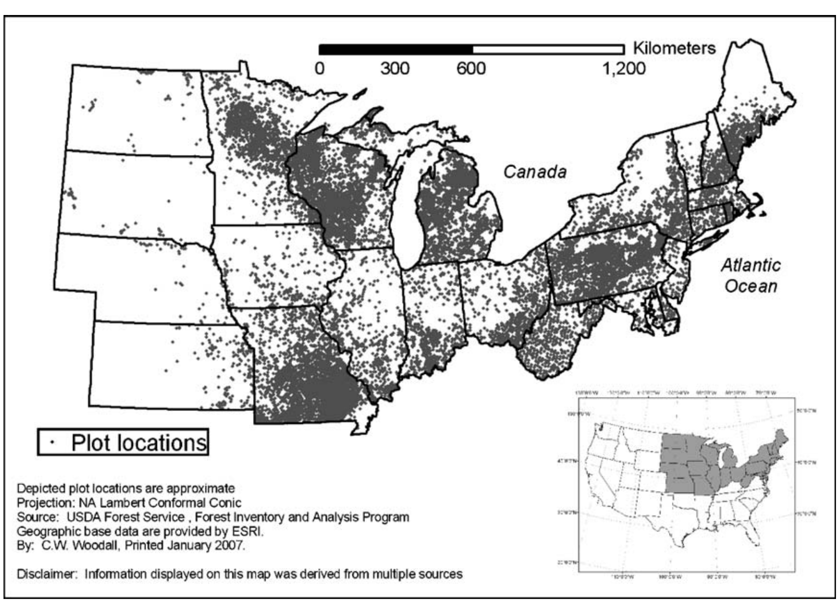

Fig. 1. Forest inventory study plots across the northeastern United States, 1999–2006. (For more information regarding state locations and name abbreviations please visit http://www-atlas.usgs.gov/).

defoliation usually is documented by a remote sensing technique known as sketch-mapping. A sketch-map is created while flying in an aircraft and observing damage and outlining its location on topographic maps. Sketch-mapping is an acquired and difficult skill that is somewhat subjective because human observers must rely on their judgement in identifying and delineating damaged areas (Johnson and Ross, 2008).

All available aerial survey data for the 24-state region were acquired for 1997–2005. The vast majority (>99%) of damages included in this dataset were delineated using aerial survey methods. The term 'aerial survey' is used throughout the study although there may be a small amount of damage that was detected using ground methods. The aerial survey damage polygons were limited to include only types of damage that would be expected to affect oak growth and/or mortality rates (branch breakage, branch flagging, defoliation, dieback, discoloration, main stem broken/uprooted, mortality, and topkill). The majority of the recorded damages were caused by one invasive, exotic insect (gypsy moth, *Lymantria dispar*). Using a Geographic Information Systems (GIS), the FIA plots were overlayed with the aerial survey damage polygons to assign each plot with the number of times damage was detected aerially (due to successive aerial surveys) during the nine year period.

2.3. Analysis

Population estimates of oak population attributes (e.g., volume, mortality, and growth) were based on procedures defined by Bechtold and Patterson (2005). Sample sizes and subsequent estimates of uncertainty varied among oak volume and mortality population estimates due to varying sample sizes (i.e., not all inventory plots have been remeasured for growth/mortality/removals). In order to provide a more sensitive indicator of oak forest health, ratios of oak mortality and standing dead trees were developed:

$$M_{\text{ratio}} = \frac{\text{Oak}_{\text{mortvol}}}{(\text{O}_{\text{akmortvol}} + \text{Nonoak}_{\text{mortvol}})} \quad (1)$$

$$\text{Sdead}_{\text{ratio}} = \frac{\text{Oak}_{\text{sdvol}}}{(\text{Oak}_{\text{sdvol}} + \text{Nonoak}_{\text{sdvol}})} \quad (2)$$

where M_{ratio} is oak mortality ratio, $\text{Oak}_{\text{mortvol}}$ is volume of oak mortality (m^3), $\text{Nonoak}_{\text{mortvol}}$ is volume of non-oak species mortality (m^3), $\text{Sdead}_{\text{ratio}}$ is the oak standing dead ratio, $\text{Oak}_{\text{sdvol}}$ is the volume of oak standing dead (m^3), and $\text{Nonoak}_{\text{sdvol}}$ is the volume of non-oak species standing dead. It is expected that the mortality and standing dead ratios will be somewhat correlated; however, standing dead ratios provide a longer temporal span of mortality assessment than the mortality ratio alone.

Due to differing levels of effort and spending among states, there is a considerable amount of variation in the detail and quality of the damage survey data across the 24-state study area. Therefore, states were assigned to 'high', 'medium', and 'low' quality categories based on the reliability of survey data. The aerial surveys were assigned to quality classes (high, medium, low) by state based on subjective assessments (USDA Forest Service, Forest Health Monitoring aerial survey quality reviews; for discussion see Johnson and Ross, 2008). Correlations were conducted using Pearson's correlation coefficients.

3. Results

Agreement between one field-based measurement of oak mortality and successive years of aerial sketch-maps for individual inventory plots was assessed using univariate statistics. There are indications that the relative mortality (oak mortality/total stand mortality) is highly skewed towards oak species constituting the majority of mortality volume in oak forests (Table 1). Over half of all observations had oak mortality accounting for over 73% of total mortality volumes. By contrast, over 75% of aerial survey observations indicated no damage over nine years of successive aerial surveys. Oak tree mortality was a common occurrence in oak forests, while the aerial detection of damage was an infrequent event.

Correlation coefficients were determined between the total number of years of detected damage by aerial survey and a host of field inventory estimates (Table 2). All correlations were very weak with only oak mortality and standing dead tree ratios having coefficients exceeding 0.15. The strongest correlations were found with overstory attributes (e.g., tree mortality) compared to understory attributes (e.g., seedlings). The effect of aerial survey quality on correlations was examined (Table 3). Stronger correlations were achieved using the highest quality aerial surveys, while both moderate and low quality surveys had weak correlations with field-based inventories. The correlation between the mortality ratio and number of years of aerially detected damage was 0.18 when using high quality survey data, but only 0.01 when using low quality aerial surveys.

Table 1
Univariate statistics of the oak mortality ratio and damage years for all plots. Order statistics for relative mortality and damage years for all plots oak forest types in the North Central and Northeastern U.S. (relative mortality: $n = 1243$, mean = 0.53, mode = 1.00: damage years: $n = 8630$, mean = 0.20, mode = 0.00).

Percentiles	Mortality ratio	Total years of damage
100 maximum	1.00	3
99	1.00	2
95	1.00	1
90	1.00	1
75 quartile 3	1.00	0
50 median	0.73	0
25 quartile 1	0.00	0
10	0.00	0
5	0.00	0
1	0.00	0
0 minimum	0.00	0

Table 2
Pearson's correlations coefficients between number of years of observed damage by aerial surveys (prior to forest inventory) and a selection of forest inventory-based stand attributes for oak forest types, North Central and Northeastern U.S.

Variables	Correlation statistics		
	Correlation coefficient	*p*-value	*n*
Oak live volume	0.00	0.9790	8575
Oak TPH, DBH > 15 cm, DBH < 300 cm	0.06	0.0001	8630
Oak TPH, DBH > 300 cm	0.10	0.0001	8630
Non-oak live volume	−0.13	0.0001	8535
Non-oak TPH, DBH > 15 cm, DBH < 300 cm	0.03	0.0017	8630
Non-oak TPH, DBH > 300 cm	−0.10	0.0001	8630
Oak volume growth	−0.04	0.0440	2697
Oak volume removals	0.00	0.9653	2697
Oak volume mortality	0.09	0.0001	2697
Non-oak volume growth	−0.11	0.0001	2697
Non-oak volume removals	0.00	0.8350	2697
Non-oak volume mortality	−0.05	0.0143	2697
Oak seedlings/ha	0.04	0.0009	5900
Non-oak seedlings/ha	0.05	0.0002	5900
Standing dead oak volume	0.07	0.0001	5680
Standing dead non-oak volume	−0.10	0.0001	5680
Mortality ratio	0.21	0.0001	1243
Standing dead ratio	0.18	0.0001	5668

TPH: trees per hectare. DBH: diameter at breast height.

Table 3
Pearson's correlations coefficients between number of years of observed damage by aerial surveys (prior to forest inventory) and a selection of forest inventory-based stand attributes by classes of aerial survey quality for oak forest types, North Central and Northeastern U.S.

Aerial survey quality	Variables	Correlation statistics		
		Correlation coefficient	*p*-value	*n*
High	Oak live volume	−0.01	0.3407	4470
	Non-oak live volume	−0.15	<0.001	4470
	Oak volume mortality	0.08	0.0012	1603
	Non-oak volume mortality	−0.03	0.1946	1603
	Standing dead oak volume	0.05	0.0031	2949
	Standing dead non-oak volume	−0.11	<0.001	2949
	Mortality ratio	0.18	<0.001	740
	Standing dead ratio	0.17	<0.001	2939
Medium	Oak live volume	−0.03	0.2209	2346
	Non-oak live volume	0.02	0.3454	2346
	Oak volume mortality	0.02	0.5569	607
	Non-oak volume mortality	0.06	0.1307	607
	Standing dead oak volume	0.03	0.2719	1563
	Standing dead non-oak volume	−0.01	0.7105	1563
	Mortality ratio	−0.03	0.6595	282
	Standing dead ratio	0.01	0.6687	1583
Low	Oak live volume	0.09	0.0005	1627
	Non-oak live volume	−0.02	0.3904	1627
	Oak volume mortality	−0.04	0.4373	452
	Non-oak volume mortality	−0.04	0.3687	452
	Standing dead oak volume	0.13	0.0001	1096
	Standing dead non-oak volume	−0.04	0.2305	1096
	Mortality ratio	0.01	0.8849	213
	Standing dead ratio	0.11	0.0003	1094

The effect of the total number of successive aerial surveys and timing between aerial and field assessments was assessed. The correlation coefficients between total years of aerially detected damage and field inventory-based mortality and standing dead volume ratios indicated that the number of aerial surveys in assessments may be important (Fig. 2). Standing dead and mortality ratios reached their highest correlation coefficients when 7 years of worth of aerial surveys were utilized with diminishing strength of coefficients as total years increased beyond 7. Aerial surveys need not detect damage in every survey year; whereas there were considerable differences in the mean

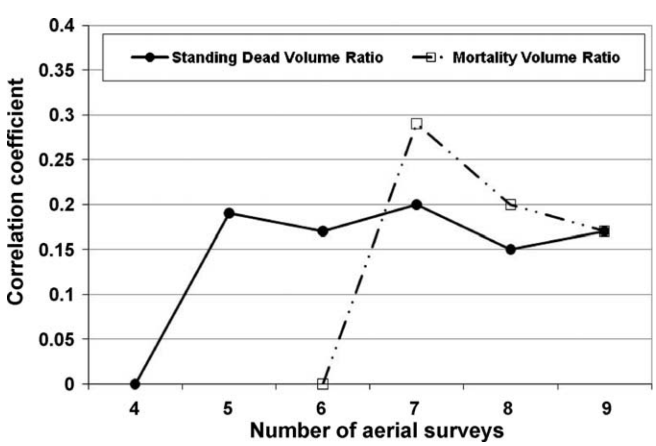

Fig. 2. Correlation coefficients (*p*-value > 0.05) between number of years of damage detected by aerial survey and field inventory assessments of ratios of tree mortality and standing dead tree volume by cumulative number of years aerial surveys conducted prior to field inventory in oak forests of the north central and northeastern U.S. Four years equal four years of consecutive aerial survey data prior to one field inventory.

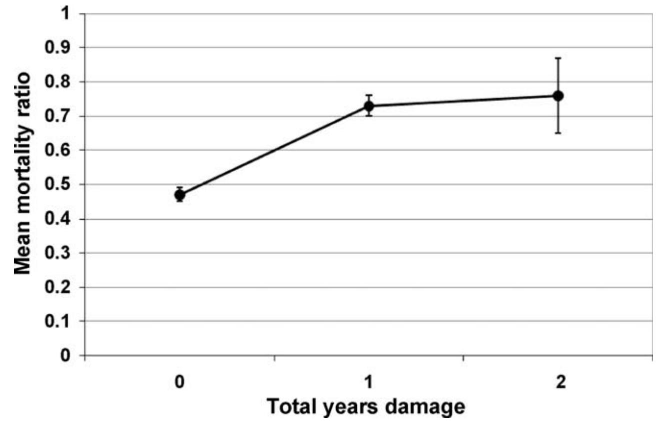

Fig. 3. Mean mortality ratios and associated standard errors by total number of years of detected aerial survey damage for inventory plots where no aerial damage was detected in 1997 for oak forests in the north central and northeastern U.S.

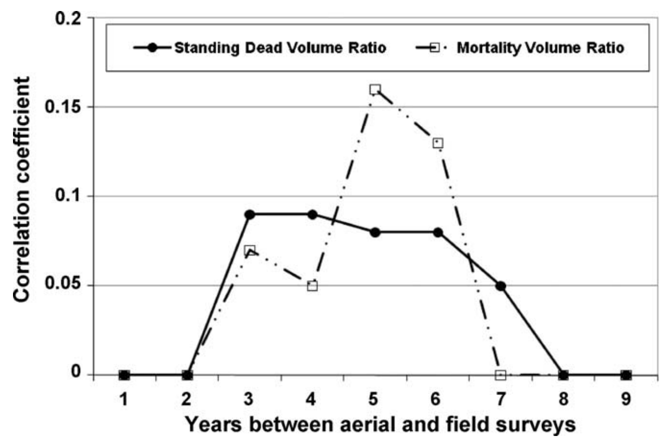

Fig. 4. Correlation coefficients (*p*-value > 0.05) between number years of damage detected by aerial survey and field inventory assessments of ratios of tree mortality and standing dead tree volume by number of years between aerial surveys conducted prior to field inventory in oak forests of the north central and northeastern U.S. Four years equal four years between an aerial survey and the subsequent field inventory.

mortality ratios between plots with no aerial detection of damage to plots where damage was detected only one year (Fig. 3). Since field inventories focus on diameter increments and tree live/dead status, how much time must pass before aerially detected damage (i.e., crown damage) is reflected in field-based inventory assessments of tree attributes (e.g., tree mortality)? The standing dead and mortality ratios achieved some of their highest correlations with aerial survey damage assessments when the time between the aerial survey and field inventory was 3–6 years (Fig. 4).

4. Discussion

Aerial surveys and field inventories are separate sampling schemes meant to indicate various aspects of forest health. The aerial surveys are an appraisal of visually obvious forest overstory damage agents for the purpose of rapid forest health assessment. Aerial surveys (aka, aerial sketch-mapping) have been noted in other studies as a very effective technique for monitoring forest defoliation, which in turn should affect subsequent forest growth and mortality (Johnson and Wittwer, 2008; Taylor and Maclean, 2008). To wit, aerial sketch-mapping of forest damage is often the first step towards employing a suite of forest health indicator field surveys to fully evaluate an emerging forest health issue. By contrast, field inventories are a systematic and more objective sampling of forest attributes for the purpose of producing population estimates. The strategic differences availed themselves when examining oak forest health in the northern United States. There were weak correlations between years of aerially detected damage and subsequent field-based forest inventory estimates. Whereas oak tree mortality is a prevalent event in forests, the obvious presence of oak damage agents in overstories was a rather infrequent event. Attempts to use aerial surveys and field inventories to estimate the same variable, such as area of oak mortality, may produce varying results as indicated in this study and should be avoided. Aerial surveys are a rather subjective and rapid observation of overstory damage agents best used to develop assessments of future tree mortality and spread of damage agents. Recent studies in Missouri have indicated that crown attributes, such as those detected by aerial surveys, are an important predictor of future oak mortality (Shifley et al., 2006; Fan et al., 2008). In contrast to aerial surveys, field-based inventories can produce statistically reliable estimates of forest resources after they have been impacted by damage agents (e.g., Kromroy et al., 2008), along with information on understory attributes such as seedlings/ saplings that determine future forest sustainability (Woodall et al., 2008). These two forest health monitoring schemes should compliment/augment each other as opposed to replication.

This study selected oak forests as the context for evaluating aerial surveys and field inventories. Undoubtedly, numerous results are oak forest centric with the selection of other forest types (e.g., maples) having the potential to affect results. The more negatively affected a forest type is by defoliators or other overstory damage agents, the greater the correlation between aerial and field inventories. With respect to oak forests, it can be postulated that overstory damage agents are probably not the primary driver of their possible decline at this broad scale. Other factors such as management activity, oak species senescence, increasing non-oak tree species competition, and droughts all combine with damage agents to produce oak mortality (for oak mortality risk discussions see Shifley et al., 2006; Fan et al., 2008). Oak forest health assessment should continue to be a mix of aerial surveys to indicate overstory damage agents, while field inventories can provide statistical estimates of the effects of damage agents on forest attributes (e.g., area, volume, and understory attributes).

Comparisons between aerial surveys and field inventories may help guide improvements in the efficacy of conducting aerial surveys. This study found that aerial surveys may be a future indicator of mortality to occur in a forest. It took approximately 5 years for aerially detected damage to be partially reflected in estimates of oak mortality. Additionally, all that was necessary was the detection of a damage agent in one year to be reflected in field observation of tree mortality. Furthermore, it was found that accumulating more than 7 years worth of continuous aerial surveys did not correlate any better with observed oak mortality. Finally, there was stark contrast in the effect of aerial survey quality on correlation with observed oak mortality. Clearly, the higher the quality of aerial survey data the higher the correlation with oak mortality. Given the expense of aerially surveying millions of hectares of forestland across the United States, the efficacy of aerial surveys and linkage with systematic field inventories may be improved by realizing cost savings from reducing aerial survey sampling intervals (e.g., bi-annually) and investing these savings in increasing spatial coverage and survey quality. Since multi-year damage events are more likely to result in growth reduction and mortality (Campbell and Sloan, 1977) a bi-annual sampling interval for damage surveys may be sufficient for capturing the most important damage events.

Finally, this study did not explore the use of high-resolution digital imagery, hemispheric photography, and/or satellite data for the assessment of forest threats and damages (for example see Coggins et al., 2008a; Goodwin et al., 2008; Coops et al., 2009; Pellikka et al., 2000). Coggins et al. (2008b) and King et al. (2005) compared varying approaches to large-scale assessment of mountain pine beetle (*Dendroctonus ponderosae*) attacks and ice storm damage finding that the optimal assessment technique may be based on the unique disturbance event and combinations of imagery/classifiers. Specific to forest decline events as examined in this study, airborne lasers have emerged as a technique for defoliation detection (Solberg et al., 2006). Despite the aerial sketch-mapping's cost efficiency and rapid deployment across large landscapes, it may be someday supplanted by emerging technologies (e.g., airborne laser or high-resolution imagery) to decrease subjectivity and increase efficiency.

5. Conclusions

In the context of indicating oak forest health across the northern United States, aerial surveys and systematic field inventories compliment but do not replicate each other. Aerial surveys are an indicator of possible future tree mortality that may be eventually detected in field inventories. Because aerial detection of forest damage is a relatively infrequent event, it may only take the detection of damage in one aerial survey for meaningful connections to be made with resulting field inventory estimates of damage impacts on forest resources. As such, the efficacy of aerial surveys may be improved by reducing survey temporal intensity, focusing on quality improvements, and increasing spatial coverage.

References

In: Bechtold, W.A., Patterson, P.L. (Eds.), 2005. Forest Inventory and Analysis National Sample Design and Estimation Procedures. Gen. Tech. Report. SRS-GTR-80. U.S. Department of Agriculture, Forest Service. Southern Research Station.

Bechtold, W.A., Tkacz, B., Riitters, K., 2007. The historical background, framework, and application of forest health monitoring in the United States. Korea Forest Conservation Movement, 2007. In: Proceedings of the international symposium on forest health monitoring, 2007 January 30–31. Seoul, Republic of Korea, p. 233, Available at http://www.srs.fs.usda.gov/pubs/27570.

Campbell, R.W., Sloan, R.J., 1977. Forest stand responses to defoliation by the gypsy moth. Forest Science Monograph, 19. Supplement to Volume 23.

Clatterbuck, W.K., Kauffman, B.W., 2006. Managing Oak Decline. University of Tennessee Extension, pp. SP–675.

Coggins, S.B., Coops, N.C., Wulder, M.A., 2008. Parameterization of insect infestation spread models using tree structure and spatial characteristics derived from high-spatial resolution digital aerial imagery. Canadian Journal of Remote Sensing 34, 485–502.

Coggins, S.B., Wulder, M.A., Coops, N.C., White, J.C., 2008. Linking survey detection accuracy with ability to mitigate populations of mountain pine beetle. Forestry Chronicle 84, 900–909.

In: Conkling, B.L., Coulston, J.W., Ambrose, M.J. (eds.), 2005. Forest health monitoring: 2001 national technical report. Gen. Tech. Rep. SRS-81. U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC. 204 p.

Coops, N.C., Wulder, M.A., Iwanicka, D., 2009. Demonstration of a satellite-based index to monitor habitat at continental-scales. Ecological Indicators 9, 948–958.

Dwyer, J.P., Cutter, B.E., Wetteroff, J.J., 1995. A dendrological study of black and scarlet oak decline in the Missouri Ozarks. Forest Ecology and Management 75, 69–75.

Fan, Z., Kabrick, J.M., Spetich, M.A., Shifley, S.R., Jensen, R.G., 2008. Oak mortality associated with crown dieback and oak borer attack in the Ozark highlands. Forest Ecology and Management 255, 2297–2305.

Goodwin, N.R., Coops, N.C., Wulder, M.A., Gillanders, S., Schroeder, T.A., Nelson, T., 2008. Estimation of insect infestation dynamics using spectral trajectories derived from a landsat time series. Remote Sensing of Environment 112, 3680–3689.

Gottschalk, K.W., 1993. Silvicultural guidelines for forest stands threatened by the gypsy moth. U.S. Department of Agriculture, Forest Service. Northeastern Research Station. Gen. Tech. Rep. NE-GTR-171.

Hickey, G.M., 2008. Evaluating sustainable forest management. Ecological Indicators 8, 109–114.

Johnson, E.W., Ross, J., 2008. Quantifying error in aerial survey data. Australian Forestry 71, 216–222.

Johnson, E.W., Wittwer, D., 2008. Aerial detection surveys in the United States. Australian Forestry 71, 212–215.

Kessler, K.J. Jr., 1989. Some perspectives on oak decline in the '80s. U.S. Department of Agricutlure, Forest Service, North Central Res. St. NC-GTR 132, 25–29.

Kessler, K.J. Jr., 1992. Oak decline on public lands in the Central Forest Region. U.S. Department of Agriculture, Forest Service, North Central Station. Res. Note. NC-362.

King, D.J., Olthof, P.K.E., Pellikka, E.D., Seed, E.D., Butson, C., 2005. Modelling and mapping damage to forests from an ice storm using remote sensing and environmental data. Natural Hazards 35, 321–342.

Kromroy, K.W., Juzwik, J., Castillo, P., Hansen, M.H., 2008. Using forest service forest inventory and analysis data to estimate regional oak decline and oak mortality. Northern Journal of Applied Forestry 25, 17–24.

Lawrence, R., Moltzan, B., Moser, W.K., 2002. Oak decline and the future of Missouri's forests. Missouri Conservationist 63, 11–18.

Manion, P.D., 1991. Tree Disease Concepts, second ed. Prentice-Hall, Englewood Cliffs, New Jersey, p. 402.

McConnell, T.J., Johnson, E.W., Burns, B., 2000. A Guide to Conducting Aerial Sketch Mapping Surveys. U.S. Department of Agriculture, Forest Service, Forest Health Technology Enterprise Team, Fort Collins, CO, p. 88, FHTET 00-01.

Morin Jr., R.S., Liebhold, A.M., Gottschalk, K.W., 2004. Area-wide analysis of hardwood defoliator effects on tree conditions in the Allegheny plateau. Northern Journal of Applied Forestry 21, 31–39.

Morin, R.S., Woodall, C., Steinman, J., Perry, C., 2009. Use of damage surveys and field inventories to evaluate oak and sugar maple health in the northern United States. comps. In: McWilliams, W., Moisen, G., Czaplewski, R. (Eds.), 2008 Forest Inventory and Analysis (FIA) Symposium, October 21–23, 2008, Park City, UTMorin, R.S., Woodall, C., Steinman, J., Perry, C., 2009.In: Proc. RMRS-P-56CD. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins, CO, 1 CD.

Nebeker, T.E., Ammon, V.D., Boyle, C.R., McCracken, F.I., Solomon, J.D., 1992. Oak Decline: A Comparison of Study Results from Different Areas of the South. Mississippi Agricultural Experiment Station, p. 19.

Oak, S., Tainter, F., Williams, J., Starkey, D., 1996. Oak decline risk rating for the southeastern United States. Annals of Forest Science 53, 721–730.

Pellikka, P., Seed, E.D., King, D.J., 2000. Modelling deciduous forest ice storm damage using aerial CIR imagery and hemispheric photography. Canadian Journal of Remote Sensing 26, 394–405.

Shifley, S.R., Woodall, C.W., 2007. The past, present, and future of Indiana's oak forests. Proceedings of the 15th Central Hardwoods Conference, February 27th–March 1, 2006. Knoxville, TN, pp. 295–304. E-Gen. Tech Rep. SRS-101.

Shifley, S.R., Fan, Z., Kabrick, J.M., Jensen, R.G., 2006. Oak mortality risk factors and mortality estimation. Forest Ecology and Management 229, 16–26.

Smith, W.B., Miles, P.D., Vissage, J.S., Pugh, S.A., 2004. Forest resources of the United States, 2002. Gen. Tech. Rep. NC-241. U.S. Department of Agriculture, Forest Service. North Central Research Station, St. Paul, MN.

Smith, W.B., Miles, P.D., Perry, C.H., Pugh, S.A., 2008. Forest resources of the United States, 2007. Gen. Tech. Rep. WO-78. U.S. Department of Agriculture, Forest Service, Washington Office. Washington, D.C., 336 p.

Solberg, S., Næsset, E., Hanssen, K.H., Christiansen, E., 2006. Mapping defoliation during a severe insect attack on Scots pine using airborne laser scanning. Remote Sensing of Environment 102, 364–376.

Starkey, D.A., Oak, S.W., 1989. Site Factors and Stand Conditions Associated with Oak Decline in Southern Upland Hardwood Forests, vol. 132. U.S. Department of Agriculture, Forest Service, North Central Res. St., St. Paul, NC-GTR, pp. 95–102.

Steinman, J.R., 2004. Forest health monitoring in the northeastern United States. U.S. Department of Agriculture, Forest Service. State and Private Forestry Technical Report. Newtown Square, PA. NA-01-04.

Taylor, S.L., Maclean, D.A., 2008. Validation of spruce budworm outbreak history developed from aerial sketch mapping of defoliation in New Brunswick. Northern Journal of Applied Forestry 25, 139–145.

Thomas, W.D., Boza, C.A., 1984. The oak decline complex. Journal of Arboriculture 10, 170–177.

U.S. Department of Agriculture, 2007. National core field guide, Version 4.0. Volume 1: field data collection procedures for phase two plots. Available at: http://www.fia.fs.fed.us/library/field-guides-methods-proc/docs/core_ver_4-0_10_2007_p2.pdf. (last accessed September 23, 2009).

Widmann, R.H., McWilliams, W.H., 2007. Changes in the oak resource in the Mid-Atlantic States (DE, MD, NJ PA, and WV) using forest inventory and analysis data. In: Society of American Foresters 2006 National Convention, October 25–29, Pittsburgh, PA.

Woodall, C.W., Grambsch, P.L., Thomas, W., Moser, W.K., 2005. Survival analysis for a large-scale forest health issue: Missouri oak decline. Environmental Monitoring and Assessment 108, 295–307.

Woodall, C.W., Morin, R.S., Steinman, J.R., Perry, C.H., 2008. Status of oak seedlings and saplings in the northern United States: implications for sustainability of oak forests. In: Proceedings of the Central Hardwoods Conference, April 8–9, 2008. Purdue University, Lafayette, IN.