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Accuracy of aerial detection surveys for mapping insect and disease disturbances in the United States

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1. Introduction

Tree injury (i.e., defoliation) and mortality from insects and diseases are annually mapped on millions of hectares of forested land in the U.S. (Potter and Paschke, 2017) (Fig. 1A and B). Due to the extent of tree injury and mortality, accurately reporting the impact of insects and diseases and other disturbances in forest ecosystems is needed to characterize current forest conditions and address and prioritize future forest management actions. In the U.S., tree mortality was primarily attributed to bark beetles (Curculionidae: Scolytinae) and defoliation was primarily attributed to spruce budworms, *Choristoneura* spp. Lederer, and European gypsy moth, *Lymantria dispar dispar* Linneaus, and these two damage categories often rival or surpass wildfire acres (Table 1). A recent study in the western U.S. has reported bark beetles impacting more canopy area than wildfires over the last three decades (Hicke et al., 2016). Bark beetles are the primary driver of tree mortality with recent outbreaks impacting forests dominated or co-dominated by loblolly pine, *Pinus taeda* L., lodgepole pine, *P. contorta* Douglas, pinyon pine, *P. edulis* Engelm., pitch pine, *P. rigida* L., and ponderosa pine, *P. ponderosa* Douglas ex C. Lawson, throughout the U.S. and in western Canada (Taylor and Carroll, 2004; Werner et al., 2006; Negron et al., 2009; Negron and Fetting, 2014; Jenkins, 2015; Harrell, 2016; Man, 2016). More frequent and severe droughts, historical fire suppression, overstocked stands, and warmer winters are further exacerbating disturbances from bark beetles and other insects and diseases (Carroll et al., 2003; Parker et al., 2006; Walker et al., 2006; Fettig et al., 2007; Bentz et al., 2010).

The USDA Forest Service, Forest Health Protection (FHP), is directed by Congress to annually report forest conditions for the U.S., primarily utilizing visual aerial surveys to map tree injury and mortality from insects, diseases, and abiotic issues, commonly referred to as aerial detection surveys, insect and disease surveys, or aerial sketchmapping (Billings and Ward, 1984). Numerous remote sensing techniques, including the use of color infrared aerial photography, high-resolution satellite and airborne hyperspectral/multispectral imagery, light detection and ranging (LIDAR) imagery, and multitemporal Landsat imagery, have been used to monitor and assess bark beetle-caused tree mortality, the impact of defoliators, and tree declines in forest ecosystems (White et al., 2005; Coops et al., 2006; Wulder et al., 2006; Heurich et al., 2010; Meigs et al., 2011; Latifi et al., 2014; Nielsen et al., 2014; Hanavan and Hallett, 2015); however, these newer technologies are currently not yet cost effective over large areas or automated to distinguish between different damaging agents and tree species for mapping annual disturbance throughout the U.S.'s millions of forested hectares.

In 2015, federal and state forest health personnel surveyed 151 million forested hectares in the U.S., 59.3% of the total forested area of the conterminous U.S. (Potter and Paschke, 2017). Aerial detection surveys have been preferred over other methodologies to monitor tree injury and mortality associated with abiotic and biotic agents due to the low cost per hectare when compared to other techniques (Harris and Dawson, 1979; McConnell et al., 2000). Tree injury and mortality are mapped primarily during the summer months and in 2004 aerial detection surveys costs were estimated at approximately \$0.025 ha^{-1} (Johnson and Ross, 2008a). Additional benefits of aerial detection surveys include quick data processing time and immediate availability for use in ArcGIS Online (ESRI, Redlands, CA, U.S.), a cloud-based mapping platform. These data are then readily available for field checking or management action following surveys, whereas other remote sensing methodologies may encounter longer post-processing

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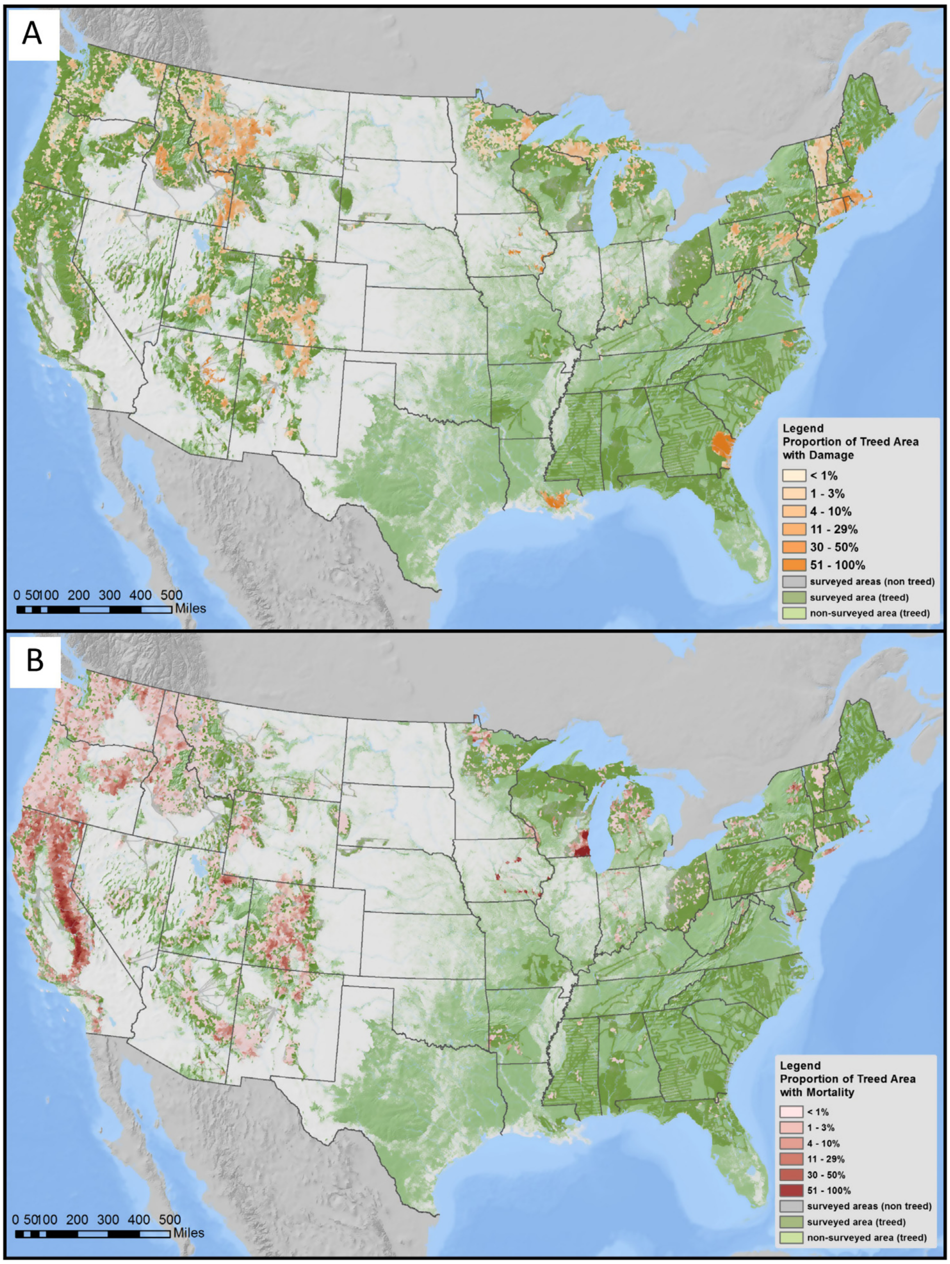

Fig. 1. Cumulative tree defoliation (A) and mortality (B) mapped in 2016 during aerial detection surveys by USDA Forest Service, Forest Health Protection and federal and state collaborators [A: Defoliation: Forest Health Protection, 2017. 2016 Damage Detection Survey by Subwatersheds (6th level HUCs). Leaflet. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Health Assessment and Applied Sciences Team. 2p. B: Mortality: Forest Health Protection, 2017. 2016 Insect and Disease Survey by Subwatersheds (6th level HUCs). Leaflet. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Forest Health Assessment and Applied Sciences Team. 2p.]

issues with imagery (e.g., cloud cover, sun angle, and delay in imagery), and ability to coordinate surveys to align with the appropriate biological window [i.e., when damage is at its peak or when injury is most visible (Fig. 2)] (Ciesla, 2000).

Early reports of aerially mapping forest insect injury date back to the 1920s when an open cockpit aircraft was used to monitor defoliation of spruce budworm, *Choristoneura fumiferana* (Clemens), in Quebec and Ontario, Canada (Swaine, 1921) and insect injury on the Sierra National Forest in California, U.S. (McConnell et al., 2000). In the 1930s, the U.S. Bureau of Entomology surveyed a bark beetle outbreak in Yellowstone National Park and F. P. Keen, an early pioneer of Forest Entomology in the western U.S., conducted an aerial survey to delineate a hemlock looper, *Lambdina fascellaria somniaria* (Hulst), outbreak in southwestern Washington (McConnell et al., 2000). Following World War II, aerial detection surveys were used more frequently due to the increased availability of aircraft and pilots (Ciesla, 2000). Aerial detection surveys have been conducted annually since 1947 in the Pacific Northwestern U.S. (Johnson, 2016) and methods to develop and improve mapping southern pine beetle, *Dendroctonus frontalis* Zimmerman, outbreaks date back to the 1950s in the southeastern U.S. (Aldrich et al., 1958; Heller et al., 1955; Billings and Doggett, 1980; Billings and Ward, 1984).

Aerial detection surveys are still invaluable in forestry today, providing qualitative and quantitative data, including damaging agents, tree species, geographic location, and intensity, of annual forest health disturbance events (Ciesla, 2000). These data largely contribute to the status and trends reported in the annual Forest Insect and Disease Condition Reports in the U.S. (USDA Forest Service, 2018). Aerial detection survey data have also provided funding justification for various FHP programs, including prevention and suppression projects for western bark beetles; assisted in delimiting the distribution of various invasive forest pests; supported State and University partners and land managers with forest management information and decisions; and provided data for the development of the USDA National Insect and Disease Forest Risk Assessment, which predicts potential basal area loss to insects and disease in the U.S. (Krist et al., 2014).