RAPID COMMUNICATION / COMMUNICATION RAPIDE

Changes in ash tree demography associated with emerald ash borer invasion, indicated by regional forest inventory data from the Great Lakes States

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Abstract: The emerald ash borer (EAB) (*Agrilus planipennis* Fairmaire) is a nonnative phloem-feeding beetle that was accidentally introduced near Detroit, Michigan, two to three decades ago. North American ash (*Fraxinus* spp.) exhibit little or no resistance, and as this insect species expands its range, extensive mortality results. Previous studies of the impacts of EAB, typical of most insect and disease impact studies, utilized data acquired from sites with known infestations and cannot be used to make regional estimates of change on forest land. By contrast, this study investigated the regional impacts of EAB on the affected resource using information from a large-scale forest inventory (Forest Inventory and Analysis program of the US Department of Agriculture, Forest Service) previously implemented to estimate regional forest resources. Results indicate that since 1980, ash has been increasing throughout many of the Great Lakes States but EAB is reversing this trend in recently invaded areas. Within 50 km of the epicenter of the EAB invasion, a major decline was observed after 2004. For growing stock (trees at least 12.7 cm diameter at breast height), average ash volume decreased from 12.7 to 3.2 $m^3 \cdot ha^{-1}$ and mortality increased from 0.1 to 1.4 $m^3 \cdot ha^{-1} \cdot year^{-1}$ on timberland between the 2004 and 2009 inventories.

Résumé : L'agrile du frêne (AF) (*Agrilus planipennis* Fairmaire) est un insecte exotique qui se nourrit du phloème et qui a été introduit accidentellement près de Détroit, au Michigan, il y a deux ou trois décennies. Les espèces nord-américaines de frêne (*Fraxinus* spp.) sont peu ou pas résistantes et, à mesure que cet insecte étend son aire de répartition, il cause beaucoup de mortalité. Les études antérieures portant sur l'impact de l'AF, typiques des études d'impact d'insectes et de maladies, ont utilisées des données provenant d'endroits où la présence de l'insecte était connue et ne peuvent être utilisées pour faire des estimations régionales des changements dans les zones boisées. Nous examinons au contraire les impacts régionaux de l'AF sur les ressources qui sont touchées en utilisant l'information provenant d'un inventaire forestier à grande échelle (le programme d'analyse et d'inventaire forestier du Service forestier des États-Unis) qui a été implanté pour estimer les ressources forestières régionales. Les résultats indiquent que depuis 1980, la présence du frêne a augmenté dans plusieurs États des Grands Lacs mais que l'AF est en train de renverser cette tendance dans les zones récemment envahies. À l'intérieur d'un périmètre de 50 km de l'épicentre de l'infestation de l'AF, un important dépérissement a été observé après 2004. Pour le matériel sur pied (arbres dont le diamètre à hauteur de poitrine est d'au moins 12,7 cm), le volume moyen de frêne a diminué de 12,7 à 3,2 $m^3 \cdot ha^{-1}$ et la mortalité a augmenté de 0,1 à 1,4 $m^3 \cdot ha^{-1} \cdot an^{-1}$ sur les terrains forestiers entre les inventaires de 2004 et 2009.

[Traduit par la Rédaction]

Introduction

Over the last 100 years, nonnative forest insects have been establishing in the United States at a rate of approximately 2.5 species per year (Mattson et al. 1994; Aukema et al. 2010). Most species are believed to arrive via accidental transport on live plants, solid wood packing material, shipping containers, or other objects associated with global trade (Work et al. 2005; Brockerhoff et al. 2006). While the vast majority of these species have caused little damage, a few of these have greatly altered the composition and structure of forests where they have become established (Liebhold et al. 1995; Kenis et al. 2009; Gandhi and Herms 2010).

The emerald ash borer (EAB) (*Agrilus planipennis* Fairmaire) provides a good example of extreme ecological and economic impacts associated with forest pest invasions (Poland and McCullough 2006). The species was initially detected in Michigan and Ontario in 2002 but that population was prob-

Received 18 January 2011. Accepted 8 September 2011. Published at www.nrcresearchpress.com/cjfr on 2 November 2011.

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ably initially established sometime in the early to mid-1990s (Siegert et al. 2009). There has been growing recognition that this insect represents a particularly serious ecological and economic problem. Female EAB lay eggs on the bark of ash trees (*Fraxinus* spp.) and larvae bore into trees where they feed on phloem and cambium, disrupting the vascular system and eventually killing host trees (Cappaert et al. 2005). The lack of resistance in North American hosts (Anulewicz et al. 2008; Rebek et al. 2008) results in rapid population growth and spread of invading EAB populations; the massive tree mortality that follows threatens the persistence of North American species in the genus *Fraxinus*.

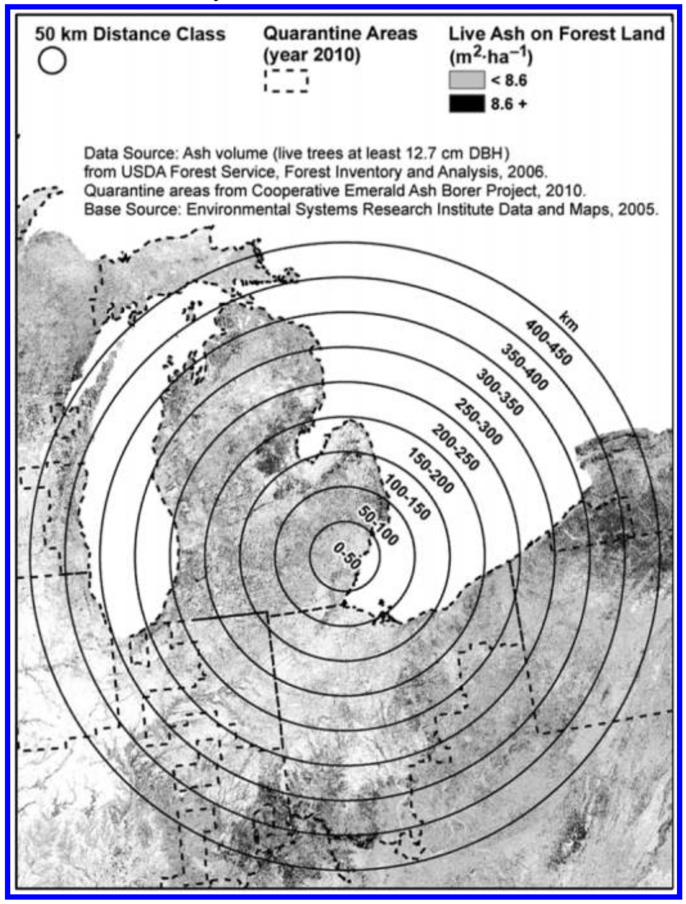
Ash trees are commonly planted in urban settings and recent analyses indicate that over the next 10 years, EAB will kill 38 million urban ash trees at a cost of $10.7 billion (Kovacs et al. 2010). In addition to urban settings, ash species are a common component of many naturally regenerating forests in the eastern and western United States. A few studies have documented ash mortality in infested stands. Gandhi et al. (2008) studied EAB impacts at selected sites in Michigan over a 4-year period and found that ash mortality steadily increased, approaching 100% in stands closest to the EAB introduction epicenter. Smith (2006) also identified a pattern of increasing mortality with decreasing distance from within 50 km of the epicenter. Smitley et al. (2008) measured dieback and mortality in selected ash trees located in southern Michigan and found that mortality and dieback were expanding from the EAB epicenter at a rate of 10 km·year^{-1} during the period 2003–2006.

While these studies provide useful information on mortality caused by EAB in selected stands, they cannot be used to quantify the impact of this pest species on a regional level. Here, we utilize data collected as part of the US Department of Agriculture, Forest Service, Forest Inventory and Analysis program (FIA) (http://www.fia.fs.fed.us/) to quantify ash mortality associated with the historical spread of EAB in Michigan and neighboring Great Lake States. These data are available at http://apps.fs.fed.us/fiadb-downloads/datamart.html. Sampling in the FIA program consists of a network of randomly located plots where standard forest inventory measurements are collected throughout the United States (Smith 2002; Bechtold and Patterson 2005; US Forest Service 2007). These data provide a unique opportunity to quantify ash mortality over regions where EAB has invaded.

Siegert et al. (2009) used dendrochronological methods to reconstruct historical spread of EAB in southern Michigan. Based on their estimates of tree mortality across a five-county region, they concluded that EAB first established in the early to mid-1990s in the Westland-Garden City, Michigan, vicinity (north of Detroit). In our study, we considered this the epicenter of EAB spread and included FIA data from Michigan, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania, and New York within a 450 km radius of the epicenter.

The FIA data records do not ascribe specific causes of mortality and likely some trees died as a result of factors other than EAB. The FIA database has general categories for the cause of death such as “insect”. We provide a brief accounting by general categories. However, because the cause of death may be unknown or may involve secondary factors, these designations cannot be definitive; consequently, most of our analyses focus on total mortality without accounting for specific agents.

Fig. 1. Location of 50 km distance (from the EAB epicenter) classes, 2010 EAB quarantine areas (broken lines), and net live ash volume (trees at least 12.7 cm DBH), Michigan, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania, and New York, 2006.



This study had several specific objectives related to quantifying the impact of EAB invasion on ash. First, we characterized baseline information about the distribution of ash in the region. An inventory of ash in Michigan, Wisconsin, Illinois, and Indiana was compiled using FIA data sampled during an approximately 20 year period leading up to 2009. After identifying estimates of ash at this large spatial scale, we used FIA data to quantify impacts at smaller scales with respect to EAB invasion. The analyses proceeded using only the most recently available data as of 2009 that included Ohio, Pennsylvania, and New York in addition to Michigan, Wisconsin, Illinois, and Indiana. We summarized the data by 50 km distance (from the EAB epicenter) classes (Fig. 1). We then focused on identifying temporal trends in ash abundance, focusing on the first two distance classes.

Methods

The FIA inventory

Under the FIA program, the US Forest Service has been collecting forest inventory data throughout the United States since 1928. The FIA program collects, analyzes, and publishes reports on all ownerships for forest land in the United States (Smith 2002). The program defines forest land as land that is at least 10% stocked with trees of any size or formerly having had such tree cover and not currently developed for nonforest use. In general, the minimum area for classification must be at least 1 acre in size and 120 feet in width. There are more specific area criteria for defining forest land near streams, right-of-ways, and shelterbelt strips (US Forest Service 2007). Timberland is forest land either producing or capable of producing crops of industrial wood and is not withdrawn from timber utilization by statute. Timberland areas are capable of producing in excess of 1.4 $m^3 \cdot ha^{-1} \cdot year^{-1}$ of industrial wood in natural stands. Inaccessible and inoperable areas are included.

Prior to 1999, FIA conducted a periodic inventory at permanent field plots approximately every 10 years. Since 1999, FIA has implemented annual inventories in which a nominal 20% of plots are visited each year (Smith 2002). After a nominal 5 years of data collection, an analysis and report are created based on the full set, or "cycle", of plots. This creates a yearly moving window of 5-year cycles and reports. The last year of each full cycle is used to name the full set of plots. For example, the cycle of plots measured from 2004 through 2009 are collectively labeled the "2009 inventory" and are used to produce a 2009 report.

Plots are randomly located in a network of hexagonal cells originally developed by the US Environmental Protection Agency's Environmental Monitoring and Assessment Program (Overton et al. 1990). There is a minimum of one plot for approximately every 2428 ha of forest land. Each plot consists of four fixed-radius subplots covering approximately 0.07 ha.

Many condition attributes (e.g., forest type, stand size, and age) and tree-level attributes (e.g., species, diameter, and height) are measured in these plots (US Forest Service 2007, 2010). The independent samples make it possible to estimate many other attributes (e.g., volume, mortality, removals, and net growth) across regions (e.g., individual states) with associated measures of reliability.

Prior to the annual inventory, data were only collected on timberland and the focus was primarily on growing-stock trees. Data are collected from all forest land in the new design. Forests in areas of urban land use are generally not sampled in the FIA program.

In cooperation with other agencies (e.g., state government), FIA also conducts the Timber Products Output (TPO) (http://www.fia.fs.fed.us/program-features/tpo/) to estimate industrial uses of roundwood such as logs, bolts, and other sections cut from trees. All primary wood-using mills in a state are canvassed every 2 years. Mills answer survey questions identifying their location, size, type, and output of roundwood products (e.g., boards, posts, poles, veneer, and pulpwood) by species/species group and county. TPO can provide an alternative estimate of harvest that can be indirectly compared with the harvest estimate from FIA plot observations.

Ash baseline inventory

To identify baseline information on ash, we analyzed available FIA data with the focus on growth, removals, mortality, and change in volume, number of trees, and area. We worked with complete sets of state-level data from more than two decades ago to 2009 for Michigan, Wisconsin, Illinois, and Indiana. For the analysis of the most recent data, we were able to examine information from forest land and add complete sets of data from Ohio, Pennsylvania, and New York. Complete data on ash from more than two decades ago are not available for Ohio, Pennsylvania, and New York but the available data indicate that the trend for these states is similar to that seen for Michigan, Wisconsin, Illinois, and Indiana.

Analysis by proximity to invasion epicenter

After identifying baseline information on ash from across most Great Lakes States, estimates of mortality, harvest, and net growth for ash were examined by 50 km distance (from the EAB epicenter) classes (nine classes, 0–450 km) using data from the 2009 inventory. We also estimated the ratio of recently dead to live ash trees by 50 km distance classes. Selection of the size for the distance classes involved several considerations related to the sample size of plots and spatial resolution. We attempted to set the width of sampling rings to include an adequate number of samples for estimation with a practical level of precision but the size was also restricted to provide adequate spatial resolution of mortality relative to distance from the EAB epicenter.

Temporal analysis

We investigated changes over time in the first four distance classes (0–200 km from the epicenter). Mortality levels above baseline estimates were identified as far away as distance class 4 (see Results: Analysis by proximity to invasion epicenter). In the first four distance classes, we investigated changes in volume, mortality, harvest, net growth, number of live trees, ratio of recently dead to live trees, and number of standing dead trees in the 2000s.

We placed special emphasis on the first two distance classes where estimates of mortality and other measures of change differed the most from the baseline estimates of the 2009 inventory (see Results: Analysis by proximity to invasion epicenter). For distance class 1, which only occurs in Michigan, we investigated changes in volume, mortality, harvest, and net growth over a longer time period, since 1980. Harvest estimates derived from FIA plot measurements in distance class 1 (see Results: Analysis by proximity to invasion epicenter) were compared with harvest information from TPO surveys of 2004 (Haugen and Weatherspoon 2010), 2006 (Piva and Weatherspoon 2010), and 2008 (pending publication).

From 2000 through 2009 for the first two distance classes, we utilized annual FIA data to generate yearly estimates of live volume and number of trees based on a nominal 20% subcycle of plots but the focus of the analysis was on general trends and not on estimates for specific years. Ninety-five percent of the plots in distance class 2 were in Michigan where the first full cycle of annual plots was measured from 2000 through 2004. An analysis of these measurements is presented in the 2004 report for Michigan (Pugh et al. 2009). The first full cycle was remeasured from 2005 through 2009. The remaining plots in distance class 2 were in Ohio where the first annual measurements started in 2001 and finished in 2006 (Widmann et al. 2009). Remeasurements from Ohio were acquired from 2007 through 2009.

Again using annual FIA data, we were able to estimate mortality, harvest, and the ratio of recently dead to live trees

Fig. 2. Number of live ash trees per hectare (at least 2.5 cm DBH) on timberland by size class and inventory for Michigan (1980, 1993, and 2009), Wisconsin (1983, 1998, and 2009), Illinois (1985, 1998, and 2009), and Indiana (1986, 1998, and 2009) (error bars represent the 95% confidence interval around the estimate).

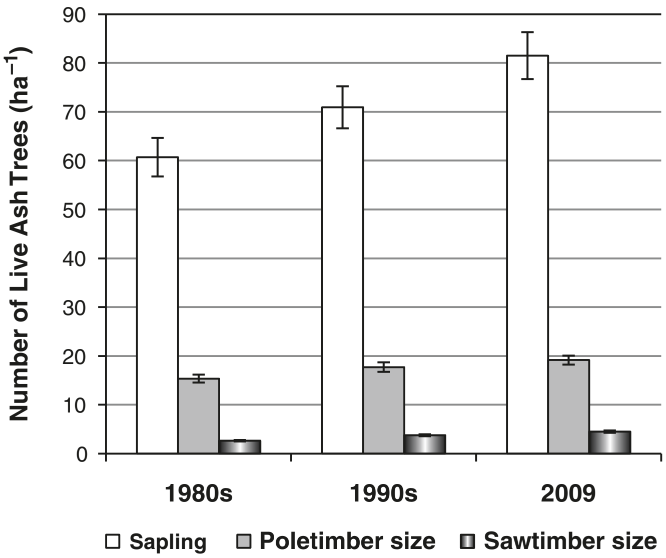
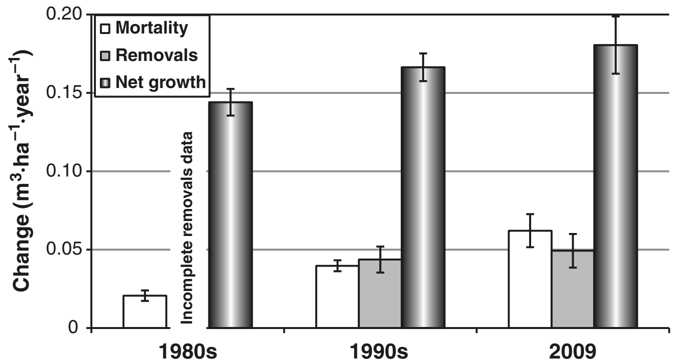


Fig. 3. Mortality, removals (harvest and land-use change), and net growth of ash growing stock (trees at least 12.7 cm DBH) on timberland by inventory for Michigan (1980, 1993, and 2009), Wisconsin (1983, 1998, and 2009), Illinois (1985, 1998, and 2009), and Indiana (1986, 1998, and 2009) (error bars represent the 95% confidence interval around the estimate).



for plots remeasured from 2005 through 2009. When analyzing change variables such as mortality and harvest collected in the FIA program, it is not possible to directly compare between successive years. Instead, the analysis must focus on a moving window of time. For example, using a 5-year cycle, if the most current measurement year for a set of plots is 2007, then the plots should have been previously measured in 2002 providing estimates of mortality from 2002 to 2007. The window moves to 2003–2008 for plots remeasured in 2008. It is best for the duration of the window to remain constant but move yearly. Unfortunately, the moving windows in this study varied due to changes in sampling intervals. In the first 50 km, the sample interval varied from 4 to 6 years per plot (versus nominal 5 years) and the number of plots sampled in a given year varied from 5 to 34 (Appendix A). Instead of an even distribution of measurements from 2005 through 2009, 69% of the plots were remeasured in 2007 and 2008.

Results

Ash baseline inventory

Across the region studied here, ash has been appearing in new locations and increasing in density since the 1980s (Fig. 2). Timberland area in Michigan, Wisconsin, Illinois, and Indiana has steadily increased by approximately 11% from the 1980s to the 2009 inventory. Timberland area with ash increased by 24% and 5% from the 1980s through the 1990s and the 1990s to the 2009 inventory, respectively.

A detailed analysis of land reverting from nonforest to forest land, referred to as reversions, across the Great Lakes States is beyond the scope of this analysis but we did examine reversions in Michigan from the 2004 to 2009 inventory. The reversions originated from a variety of land uses, in descending order: water–marsh–wetland (25%), farmland (25%), developed–cultural (25%), pasture–rangeland (14%), rights-of-way (6%), and other (5%). This distribution of reversions with ash does not appear to differ from the distribution of reversions that includes all tree species. Including all tree species, reversions came from water–marsh–wetland (28%), farmland (24%), developed–cultural (22%), pasture–rangeland (16%), rights-of-way (5%), and other (5%).

The number of ash trees per hectare on timberland also increased in sapling-, pole-, and sawtimber-size trees (Fig. 2; US Forest Service 2007). Saplings are at least 2.5 cm diameter at breast height (DBH). Poletimber-size trees are at least 12.7 cm DBH and less than 22.9 and 27.9 cm DBH for softwoods and hardwoods, respectively. Sawtimber-size trees are at least 22.9 and 27.9 cm DBH for softwoods and hardwoods, respectively. This resulted in a 48% increase in the number of ash trees (at least 2.5 cm DBH) and an 84% increase in the volume of ash growing-stock trees on timberland from the 1980s to the 2009 inventory. Growing-stock trees are live trees at least 12.7 cm DBH and meet minimum merchantability standards. In general, these trees have at least one solid 2.4 m section, are reasonably free from defect on the merchantable bole, and at least 34% of the volume is merchantable. Prior to the 2000s, most FIA estimates were for growing-stock trees on timberland. Across much of the region, ash has been appearing in new locations and increasing in density. Average annual net growth (growth minus mortality) and mortality have risen with the increase in trees and volume (Fig. 3).

Michigan, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania, and New York had approximately 8.6 $m^3 \cdot ha^{-1}$ of ash (sound volume of live trees at least 12.7 cm DBH) on forest land in the 2009 inventory. The associated average annual mortality, removals (harvest and land-use change), and net growth were 0.1, 0.1, and 0.2 $m^3 \cdot ha^{-1}$, respectively, in the 2009 inventory. For most states, it is only possible to differentiate harvest and land-use change removals in the most recent data. Whenever possible in this study, harvests are identified. The ratio of recently dead to live trees (at least 12.7 cm DBH) was 0.06.

Ash species are widely distributed through the region with a few specific regions of particularly high density (Fig. 1). These areas include the central Lower Peninsula of Michigan,

Fig. 4. Average annual mortality, harvest, and net growth of ash (sound volume of trees at least 12.7 cm DBH) on forest land by distance to the EAB epicenter, Michigan, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania, and New York, 2009 inventory (error bars represent the 95% confidence interval around the estimate).

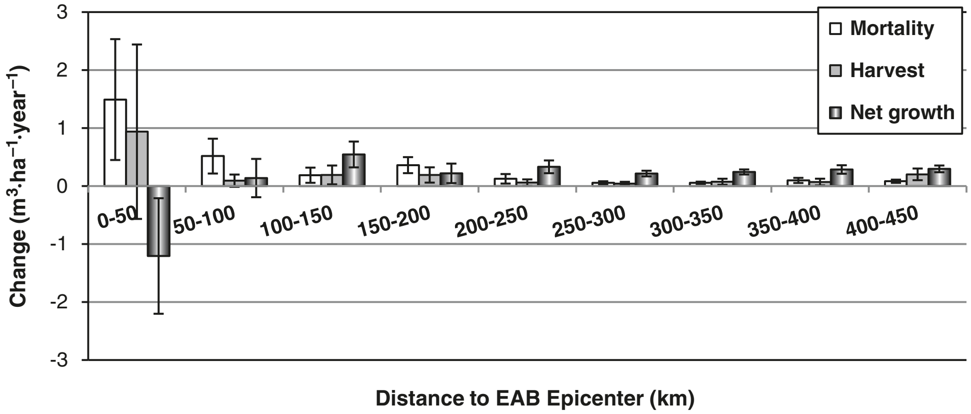
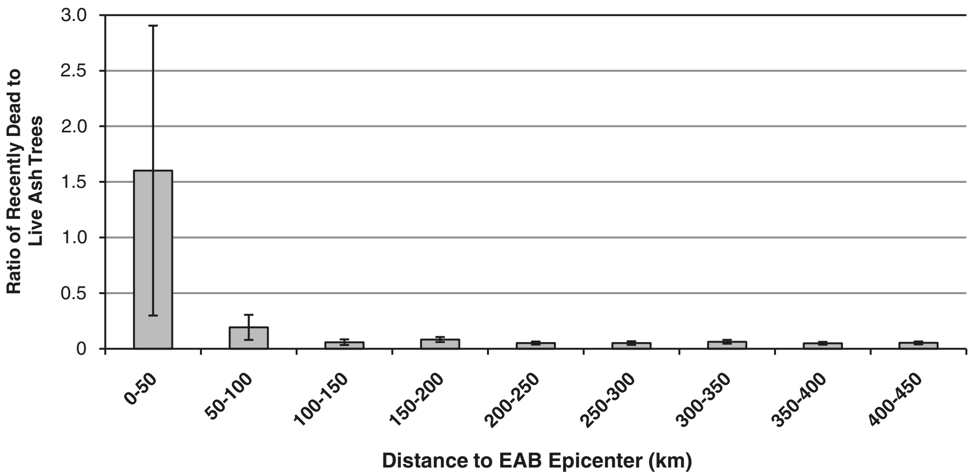


Fig. 5. Ratio of recently dead to live ash trees (at least 12.7 cm DBH) on forest land by distance to the EAB epicenter, Michigan, Wisconsin, Illinois, Indiana, Ohio, Pennsylvania, and New York, 2009 inventory (error bars represent the 95% confidence interval around the estimate).



western New York, north-central Pennsylvania, and southern Ohio and Indiana. For Fig. 1, estimates of live ash volume (net volume of trees at least 12.7 cm DBH) on forest land were produced in a raster model using nearest neighbor-imputation with methods adapted from Ohmann and Gregory (2002). Estimates of volume derived from FIA field measurements were assigned to 250 m resolution pixels using 250 m Moderate Resolution Imaging Spectroradiometer imagery, 30 m National Land Cover Dataset imagery, and climate and topographic data. The raster model is designed to make estimates at scales approximating a county (30 km × 30 km) or preferably larger. The model estimates are dependent on available imagery. Years associated with the input data for the model range from 2001 (National Land Cover Dataset imagery) to 2006 (FIA data), resulting in a coarse temporal resolution.

Analysis by proximity to invasion epicenter

For sound volume on forest land in the 2009 inventory, estimates of mortality in distance classes 1 (1.5 $m^3 \cdot ha^{-1} \cdot year^{-1}$, $0.003 < p < 0.01$), 2 (0.5 $m^3 \cdot ha^{-1} \cdot year^{-1}$, $0.003 < p < 0.02$), and 4 (0.4 $m^3 \cdot ha^{-1} \cdot year^{-1}$, $0.003 < p < 0.05$) were significantly greater than the baseline estimate (0.01 $m^3 \cdot ha^{-1} \cdot year^{-1}$) (Fig. 4). The ratios of recently dead to live ash trees (at least 12.7 cm DBH) in distance classes 1 (1.6 ratio, $0.003 < p < 0.01$) and 2 (0.2 ratio, $0.003 < p < 0.05$) were significantly greater than the baseline estimate (0.06 ratio) (Fig. 5). Net growth of sound volume in distance class 1 (–1.2 $m^3 \cdot ha^{-1} \cdot year^{-1}$, $p < 0.001$) was significantly less than the baseline estimate (0.2 $m^3 \cdot ha^{-1} \cdot year^{-1}$) (Fig. 4).

The estimate for harvest of sound volume on forest land (0.9 $m^3 \cdot ha^{-1} \cdot year^{-1}$) in the first 50 km was not significantly greater than the baseline estimate at the 95% confidence interval but was significantly greater at the 68% confidence interval ($0.05 < p < 0.16$).

As previously mentioned, FIA inventories do not record specific causes of death such as EAB. The available general categories are as follows: insect, disease, fire, animal, weather, vegetation, silvicultural treatment, and unknown. For distance classes 5–9 (200–450 km), the cause of death for each tree was predominantly (77%) unknown. For this same area, 2% of the deaths were attributed to insects. In contrast, 80%, 69%, 15%, and 8% of the deaths were attributed to insects in the first, second, third, and fourth distance

Fig. 6. Volume of live ash growing stock (trees at least 12.7 cm DBH) on timberland within 50 km of the EAB epicenter by inventory, Michigan (error bars represent the 95% confidence interval around the estimate).

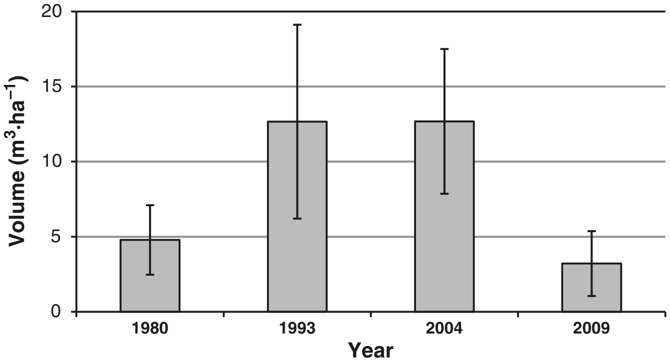
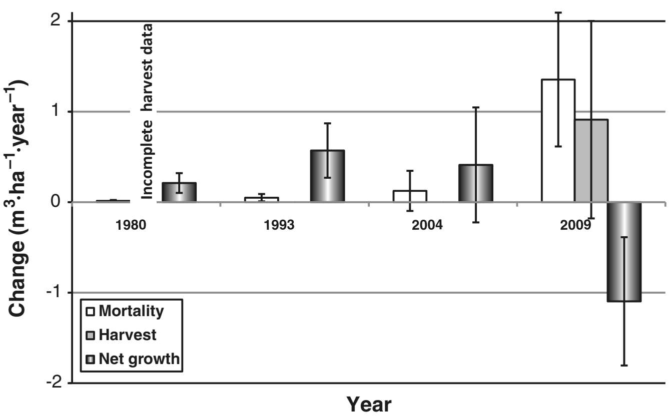


Fig. 7. Average annual mortality, harvest, and net growth of ash growing stock (trees at least 12.7 cm DBH) on timberland within 50 km of the EAB epicenter by inventory, Michigan (error bars represent the 95% confidence interval around the estimate).



classes, respectively. The cause of death was unknown in 20%, 28%, 55%, and 52% of the cases in the first, second, third, and fourth distance classes, respectively.

If EAB started killing large numbers of trees around 1998, then the average annual estimates in distance class 1 should include approximately 8 years of observed mortality caused by EAB. This takes into account a number of facets of FIA methodologies such as when trees were previously measured, the fact that mortality is not recorded for dead trees on new plots, and that mortality is only counted the first time it is observed on remeasured plots.

Temporal analysis

On timberland, change in volume of ash growing stock in distance class 1 from the 1980 to 1993 inventory (Fig. 6) was similar to the trend of increasing abundance seen throughout most of the Great Lakes States from the 1980s to the 1990s (Fig. 2). Estimates of mortality, net growth, harvest, and volume in distance class 1 were essentially the same as from the 1993 to 2004 inventory (Figs. 6 and 7). But for growing stock from the 2004 to 2009 inventory, volume, number of trees, and net growth decreased from 12.7 to 3.2 m^3·ha^{-1} ($0.003 < p < 0.05$), from 43.3 to 12.7 trees·ha^{-1} ($0.003 < p < 0.05$), and from 0.4 to –1.1 m^3·ha^{-1}·year^{-1} ($0.003 < p < 0.05$), respectively. Mortality of growing-stock trees increased from 0.1 to 1.4 m^3·ha^{-1}·year^{-1} ($0.003 < p < 0.05$) and harvest levels rose from zero samples to an estimate of 0.9 m^3·ha^{-1}·year^{-1}. Standing dead trees on timberland (at least 12.7 cm DBH) also increased from 8.6 to 24.2 trees·ha^{-1} ($0.003 < p < 0.05$). In distance class 2 and only in Michigan (estimates of mortality, harvest, and net growth from the 1990s to early 2000s are not available at this time for Ohio), there was a significant increase in mortality of growing-stock trees on timberland from the 2004 to 2009 inventory (0.1 to 0.4 m^3·ha^{-1}·year^{-1}, $0.003 < p < 0.05$). There were no other significant changes identified in the first four distance classes.

In distance class 1 where harvests rose, the distribution of harvest among ash species for the 2009 inventory was similar to the distribution of total volume among ash species for the 2004 and 2009 inventories. For the 2004 inventory, the distribution of sound volume by species was 27%, 7%, and 67% for white (*Fraxinus americana* L.), black (*Fraxinus nigra* Marsh.), and green ash (*Fraxinus pennsylvanica* Marsh.), respectively. The distribution of harvest of sound volume by species for the 2009 inventory was 28%, 0%, and 72% for white, black, and green ash, respectively.

The TPO includes harvest information from all land types (nonforest and forest land) summarized by county and ash species group (individual species are not delineated). The TPO survey of mills for counties in the first 50 km around the epicenter (Livingston, Macomb, Monroe, Oakland, Washtenaw, and Wayne counties) recorded harvest levels (0.0001 m^3·ha^{-1}·year^{-1} for 2004 through 2008) that were a small fraction of the harvest estimates (sound volume of 0.9 m^3·ha^{-1}·year^{-1}) derived from FIA plot measurements for the 2009 inventory on forest land.

A year-to-year breakdown of the 2004 and 2009 inventories provided a more detailed depiction of change in the first two distance classes (Table 1). Even though sample sizes were too small to be precise, yearly estimates of variables such as sound live volume and number of trees per hectare (at least 12.7 cm DBH) in the first distance class show a declining trend after 2004. In this case, the number of live trees appears to be a more robust indicator than volume. There were two outliers in the 2008 measurement year, the two largest live ash trees (greater than 48.3 cm DBH), that affected sound live volume per hectare. Removing these two samples for 2008 decreased the volume estimate from 6.0 to 2.7 m^3·ha^{-1}. The number of live ash decreased from 19 to 17 trees·ha^{-1}.

We found no clear trend of increasing mortality or harvest of ash trees when examining estimates of sound volume for the moving windows associated with plots remeasured from 2005 through 2009 (Table 2). Inconsistent sampling size and frequency may have precluded our ability to identify any clear trend in the first distance class. The previously mentioned outliers that affected live volume per hectare also affected the average annual mortality to current volume estimates. Removing the outliers raised the average annual mortality to current volume from 29% to 65% for 2008. Similar to the effects observed on number of live trees per hectare, the ratio of recently dead to live trees (at least 12.7 cm DBH) only rose from 1.5 to 1.6 after removing the outliers.

Table 1. Estimates of live ash sound volume and number of trees (at least 12.7 cm DBH) on forest land with sample sizes for the first two distance classes by measurement year.

Distance to EAB epicenter (km)	Measurement year	All plots	Ash plots	Ash (trees sampled)	Ash ($m^3 \cdot ha^{-1}$)	Ash ($trees \cdot ha^{-1}$)
0–50	2001	22	11	53	7	42
	2002	25	13	86	23	80
	2003	51	23	84	13	33
	2004	21	14	49	14	44
	2005	8	0	0	0	0
	2006	15	5	7	2	9
	2007	32	13	26	3	16
	2008	27	7	24	6	19
	2009	5	2	2	1	11
50–100	2000	25	10	38	10	27
	2001	65	41	183	16	50
	2002	81	41	198	13	42
	2003	166	93	512	18	56
	2004	78	41	212	16	50
	2005	57	28	115	11	36
	2006	43	29	121	18	57
	2007	120	62	259	19	44
	2008	69	35	175	17	46
	2009	29	13	40	7	27

Despite no clear trend, mortality and harvest estimates were much higher than those in other parts of the region.

Discussion

There is a limited precedent for the use of regional forest inventory data to quantify pest impacts. Shaw et al. (2005) used FIA data to quantify massive amounts of pinyon pine (*Pinus edulis* Engelm.) mortality across a four-state region in response to drought and associated bark beetle outbreaks. Gansner et al. (1993) analyzed FIA data collected across the Pocono Mountains region in 1965 and remeasured in 1989, a period during which two large gypsy moth (*Lymantria dispar* L.) outbreaks occurred across the region. While they found unusually high levels of mortality in oak, the primary host of the gypsy moth, they also found that total oak volume increased during that same period, suggesting that the net effect of the gypsy moth defoliation had been minimal. In a study more similar to that described here, Morin et al. (2007) analyzed the accumulation of standing dead American beech (*Fagus grandifolia* Ehrh.) relative to the number of years during which beech bark disease had invaded counties across the eastern United States. They found elevated densities of dead beech associated with the presence of the disease, but across all regions, including those with the longest presence of the disease, beech volume increased. The declines in ash volume associated with EAB invasion reported here thus are indicative of a stronger trend of regional decline in volume associated with invasion by this aggressive tree-killing insect.

Although it is generally accepted that millions of ash trees have died within urban and forested areas in Michigan, there is relatively little information in the literature documenting such damage. Perhaps the most extensive study to date was conducted at a series of 31 forest stands within the Huron River Watershed in southeast Michigan (Oakland, Livingston, and Washtenaw counties) located within 24–48 km of the epicenter (Smith 2006). In each of three remeasurements (2004–2005, 2006, and 2007), ash mortality progressively increased, and in each year, mortality declined with distance from the EAB epicenter (Gandhi et al. 2008). By 2007, ash mortality ranged from 80% to 100% for stands located within 30 km of the EAB epicenter. These levels are generally consistent with data on ash mortality reported here; however, it should be pointed out that the plots used by Gandhi et al. (2008) were not located in a random fashion and thus not ideal for estimation of regional impacts. Even though plot densities create some problems, the statistically based random plot design of the FIA program provides a unique opportunity for assessing trends in forest composition across regions over time.

Ash has increased in abundance and size throughout many of the Great Lakes States since 1980 (Figs. 2 and 3). The recent decreases in ash abundance and volume in areas where EAB has become recently established are in stark contrast with the increases in ash that are occurring elsewhere. Within 50 km of the EAB epicenter, FIA estimates associated with the 2004 inventory showed no change in volume since 1993, counter to the increasing trend in most Great Lakes States. Then conditions worsened in the first distance class with a significant decline between the 2004 and 2009 inventories.

In distance class 2, it appears that EAB is also having a noticeable impact given the increase in mortality and the relatively high mortality and ratio of recently dead to live trees as compared with baseline estimates derived from most of the Great Lakes States. Significant decreases in volume and net growth are expected to follow quickly in distance class 2.

Although outlier EAB populations are known to exist at longer distances (Kovacs et al. 2010), the mortality, harvest, and net growth estimates for greater distance classes, besides distance class 4 (150–200 km), were not significantly greater than the baseline estimates. In distance class 4, the relatively high mortality per hectare was the only estimate possibly in-

Table 2. Comparison of average annual mortality and harvest (sound volume of trees at least 12.7 cm DBH) and ratio of recently dead to live ash trees (at least 12.7 cm DBH) on forest land for the first two distance classes by remeasurement year.

Distance to EAB epicenter (km)	Remeasurement year	Ratio of annual mortality to current volume (%)	Annual mortality ($m^3 \cdot ha^{-1}$)	Ratio of annual harvest to current volume (%)	Annual harvest ($m^3 \cdot ha^{-1}$)	Ratio of recently dead to live
0–50	2005	No live volume	2.6	No live volume	2.0	No live volume
	2006	139	2.3	6	0.1	2.1
	2007	20	0.5	67	1.6	0.9
	2008	29	1.9	6	0.4	1.5
	2009	552	3.8	0	0.0	6.5
	2005–2009	44	1.5	27	0.9	1.6
50–100	2005	2	0.3	0	0.0	0.1
	2006	1	0.1	2	0.2	0.0
	2007	3	0.7	0	0.0	0.2
	2008	3	2.0	0	0.3	0.2
	2009	18	1.7	1	0.1	0.6
	2005–2009	3	0.5	1	0.1	0.2

dicating an issue beyond the baseline estimates. Presumably, most of these areas remain uninfested and (or) recently infested areas have such low levels of mortality that we were not able to identify impacts in these higher distance classes. A further breakdown of the greater distance classes by state did reveal greater than normal levels of mortality and harvest for some areas, but the sample sizes were small, creating considerable uncertainty in the estimates. Similarly, the small sample sizes in the first distance class and in the year-to-year analysis made identifying trends difficult.

In the first distance class, ash harvests for the 2009 inventory were high, almost as high as the volume of nonharvested mortality (Fig. 7). Some EAB management guidelines recommend presalvage or salvage of trees in or near infested areas (e.g., Wisconsin Department of Natural Resources 2010) and there have been ongoing efforts to utilize ash in southeast Michigan. With support from the US Forest Service Northeastern Area State and Private Forestry Wood Education and Resource Center, the Southeast Michigan Resource Conservation and Development Council (2010) provided funds to increase processing capabilities and bring together urban (not forest land) wood suppliers with users.

In the first 50 km around the epicenter, the TPO offered alternative estimates of harvest that were much lower than those derived from FIA plot measurements. This indicates that much of the harvest is not going to traditional mills and possibly not to traditional products (e.g., high-quality sawtimber-size white ash trees for furniture and smaller or lower quality white and green ash trees for pallets and railroad ties). The quarantine boundaries restricted movement of ash to mills. Furthermore, the market for ash was not favorable during most of the 2000s (A.K. Weatherspoon, personal communication, 2011) and lower quality trees and those smaller than sawtimber size are normally not worth moving long distances. It is expected that much of the harvest was used for fuel, thus explaining why it was not evident in TPO data.

As EAB expands its range, the area of newly infested forest can be expected to grow approximately geometrically (Kovacs et al. 2010). As the opportunity for salvage and presalvage increases, it is uncertain whether a high level of harvest can be maintained throughout affected regions. We anticipate that domestic quarantines prohibiting movement will be a factor limiting markets for ash cut as part of either sanitation or salvage operations. Demand for ash timber in local areas may become saturated and such salvage and presalvage activity may become proportionally smaller.

Although EAB was probably introduced in the early to mid-1990s (Siegert et al. 2009), our analysis did not show a decrease in live volume or number of ash trees per hectare until after 2004 within 50 km of the epicenter (Table 1). This may be due to a lag in time between the introduction of EAB and the increase of populations capable of causing high amounts of mortality and or partly due to the nature of the FIA inventory. There were no FIA data collected in Michigan between 1993 and 2000. Using FIA data, it would have been unlikely that a forest health issue could have been detected even in the early 2000s because the estimates of change were based on initial samples in 1993. It may have been possible to identify a decline in ash in the early 2000s if the annual collection had started in the mid-1990s.

There were difficulties discerning recent temporal trends in the moving windows for mortality and harvest. Perhaps due to the inconsistent sample size and frequency (Appendix A), there was no evidence of a decrease in mortality in the first distance class (Table 2), but with continued decreases in volume, the rate of mortality may begin to slow in areas that have been infested the longest.

To identify forest health issues, many types of estimates can be derived from FIA data. This study calculated a number of estimates. Considering the small sample size in the first distance class and the year-to-year temporal analyses, sensitivity of the estimates to outliers, and the indifference of EAB to tree size, changes in the number of live trees and the ratio of recently dead to live trees (at least 12.7 cm DBH) appeared to be the most robust estimates for characterizing the forest health issue highlighted here.

As EAB continues to spread through the United States, annual FIA data will continue to be useful for identifying impacts in a timely manner. For example, once impacts have continued to expand over several years, it should be possible to identify rates of spread based on patterns of tree mortality. FIA data could be of critical importance for identifying temporal trends in the distribution of mortality among diameter classes and critical for answering questions about the composition and resistance of forests remaining in the aftermath of the EAB invasion wave. Work is also ongoing to investigate the use of FIA data for identifying pockets of tree mortality associated with new EAB outlier infestations.

Acknowledgements

We wish to thank Jennifer Koch, Research Biologist with the US Forest Service, Northern Research Station, and Kathleen Knight, Research Ecologist with the US Forest Service, Northern Research Station, for comments on an earlier version of this manuscript. We also thank Anthony Weatherspoon, Forest Products Specialist with the Michigan Department of Natural Resources, for answering questions concerning ash in the economic market.

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Appendix A

Table A1 appears on the following page.

Table A1. Number of sample trees (at least 12.7 cm DBH) on forest land for estimates of mortality, harvest, and net growth for the first two distance classes by remeasurement year.

Distance to EAB epicenter (km)	Remeasurement year	All plots remeasured	Plots with ash remeasured	Maximum remeasurement interval (year to year) of ash	Average remeasurement interval (years) of ash	All trees remeasured	Ash trees remeasured
0–50	2005	8	3	2000–2005	4.3	108	11
	2006	15	8	2001–2006	4.5	229	14
	2007	34	15	2001–2007	5.2	559	72
	2008	27	14	2002–2008	5.1	392	66
	2009	5	2	2004–2009	4.8	45	8
	2005–2009	89	42		5.1	1333	171
50–100	2005	54	27	2000–2005	4.2	1006	118
	2006	43	29	2000–2006	4.4	775	138
	2007	113	61	2000–2007	5.0	2073	277
	2008	63	35	2002–2008	4.9	1192	205
	2009	24	15	2004–2009	4.9	368	56
	2005–2009	297	167		4.7	5414	794

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