Emerald Ash Borer (*Agrilus planipennis*): Towards a Classification of Tree Health and Early Detection

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Abstract. Forty-five green ash (*Fraxinus pennsylvanica*) street trees in Toledo, Ohio were photographed, measured, and visually rated for conditions related to emerald ash borer (*Agrilus planipennis*)(EAB) attacks. These trees were later removed, and sections were examined from each tree to determine the length of time that growth rates had been impacted. A classification system was developed to discern the health of the trees along with a proposed method for early detection of a declining state of vigor. The classification is not an indicator of the degree of infestation, but rather tree health, which may be linked to the degree of EAB infestation. An evaluation of the tree sections places the EAB establishment no later than the 2004 growing season. A three-class system formulated from the evaluation of epicormic shoots, canopy light transmission, and EAB exit holes can be used to monitor the health of ash trees during EAB outbreaks. The classification system could potentially give homeowners, property managers, and agencies a way to detect and treat this problem earlier, especially in urban and park settings, and before trees are fully infested and exhibiting later-stage signs of decline. It is probably not practical for forest applications. Early detection and treatment not only can save selected trees, but it also might slow the spread of the insect, thereby giving additional trees a chance to survive the initial invasion.

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INTRODUCTION

The Emerald Ash Borer (EAB) has been primarily responsible for the recent decline and death of millions of native ash (*Fraxinus spp.*) trees in Michigan (first discovered in 2002), Ohio and Ontario (2003), Indiana (2004), Illinois and Maryland (2006), Pennsylvania and West Virginia (2007), Missouri, Quebec, Virginia (VA DOA 2008), and Wisconsin (2008), and Minnesota (2009) (USDA APHIS 2009). According to the U.S. Department of Agriculture's Animal and Plant Health Inspection Service (USDA APHIS), the insect was first discovered near Detroit, MI, in 2002, but evidence collected by Siegert and others (2006) indicates that EAB establishment probably occurred in the early 1990s. Cappaert and others (2005), Iverson and others (2008), and Prasad and others (2010) estimated its first significant kills occurred in about 1998 based on available data and dispersal patterns. An estimated eight billion ash trees exist in the United States, comprising roughly 7.5 percent of the volume of hardwood sawtimber, 14 percent of the urban leaf area (as estimated across eight U.S. cities), and valued at more than $300 billion (Poland and McCullough 2006).

In Ohio forests, white ash (*Fraxinus americana)* is counted the third most abundant (number of stems) species with only sugar maple (*Acer saccharum*) and American elm (*Ulmus americana*) being more abundant, based on U.S. Forest Service Forest Inventory and Analysis (FIA) data (Prasad and others 2007). Green, and especially black, pumpkin, and blue ash (*F. pennsylvanica, F. nigra, F. profunda, and F. quadrangulata*, respectively) are less abundant in the state. However, in the City of Toledo, green ash was the dominant ash species (Sydnor and Subburayalu 2008). All ashes together in Ohio account for an estimated nine percent of the total number of trees sampled by the U.S. Forest Service (Miles and others 2001). The percent ash basal area in the woodlands of rural northwestern Ohio (e.g., Toledo region) is the highest in the state, so that the EAB devastation will have a larger ecological and socioeconomic impact in that region (Sydnor and others 2007).

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Since the discovery of EAB in the United States, much research has been conducted to help land managers, agencies, and municipalities deal with this exotic pest invasion. Currently, there are few ways of detecting EAB during the colonization phase. Detection relies primarily on visual surveys of late stage symptoms. At low to moderate densities of EAB, visual surveys are unreliable (Poland and McCullough 2006). Detection trees (i.e., girdled and sticky-trapped trees) have also been used to detect new EAB populations throughout Ohio (e.g. ~9670 trap trees placed in 2007, 9000+ in 2006). In 2008, purple sticky prism traps were deployed throughout Ohio. Detection trees and sticky-traps only confirm the presence of EAB within the area after the initial infestation and do not identify which trees are infested.

Symptoms of an EAB attack include crown dieback, splitting of the bark, woodpecker damage, loss of foliage density, presence of D-shaped exit holes and epicormic shoots (Cappaert and others 2005). These symptoms, however, are usually more prevalent in well-established infestations where a tree's health has been severely degraded. Ash yellows, a disease caused by a mycoplasma-like organism that went unreported until the 1980s, results in several symptoms of decline similar to those associated with early EAB attack (Pokorny and Sinclair 1994). Trees lightly infested with EAB can be treated with reasonable success but with ongoing costs, while severely attacked trees have a limited chance of survival and will need to be removed in urban environments. Our objective was to develop a rating of tree health related to vigor that would be non-destructive and would provide homeowners and property managers information on which to base management decisions such as whether to treat or remove. This index should not be considered as a measure of infestation, nor is it intended for forest applications.

METHODS

Field Data Collection

We selected Toledo for this study because of its primary location in Ohio's EAB infested zone and its large population of ash street trees that have various degrees of EAB damage. Toledo's Department of Parks, Recreation and Forestry scheduled the removal of all ash trees on Gracewood Road in the fall of 2006 and Bellevue Street in 2007, due to the presence of EAB. The ash trees on Gracewood and Bellevue had been planted to replace elm (*Ulmus sp.*) trees following the 1950-60s outbreaks of Dutch Elm Disease. They were therefore roughly similar in size. Fifteen green ash (*F. pennsylvanica*) trees on Gracewood and 30 on Bellevue were selected for further evaluation based on varying severities of symptoms of EAB damage. Collected data included a count of epicormic shoots and D-shaped exit holes, hemispherical and multiple canopy photographs, and measurements of diameter, height, and twig extension growth of the trees (Table 1).

On 14 September 2006, diameter at 1.4 m (DBH) and tree height were measured for each selected tree along Gracewood. Epicormic shoots longer than 15 cm were counted from the tree base to a height of 4.9 m. D-shaped exit holes were counted on each tree bole within four 25 x 25 cm quadrats placed in the four cardinal directions within a sampling area (between 1.2 and 1.8 m above the tree base). Each quadrat was randomly placed and excluded the possibility of overlap in the exit hole evaluation area among the four quadrat samples. Hemispherical photographs (digital images of 3264 x 2448 pixels with a fish-eye lens) for each tree were taken vertically into the canopy to quantitatively assess canopy density related to light transmission. All trees were located between the sidewalk and curb and grew among oaks (*Quercus sp.*), maples (*Acer sp.*), and other overstory hardwoods.

During the week of 23 October 2006, the trees on Gracewood were felled, and branches and cross sectional disks (cookies) were recovered for further analysis. Cookies along the dominant leader

Table 1

Values for the 45 sampled trees collected from Gracewood (2006) and Bellevue (2007). Percent Light transmission was calculated using Gap Light Analyzer software on hemispherical photos for Gracewood and telephoto images for Bellevue. The ATHI scores > 20 rate poor, 10-20 rate intermediate, and < 10 rate good.

ID	Street	DBH (cm)	Ht. (m)	Exit Holes	Epicormic Shoots	Light Trans.	ATHI Value	ATHI Class
241	Gracewood	53	19	3	87	20.3	36.8	Poor
242	Gracewood	39	18	0	0	7.2	3.6	Good
243	Gracewood	48	20	5	66	13.6	27.6	Poor
244	Gracewood	53	21	1	61	22.4	29.7	Poor
245	Gracewood	36	18	0	39	16.1	19.7	Inter.
246	Gracewood	48	21	6	14	20.1	15.5	Inter.
247	Gracewood	55	20	5	13	27.5	18.7	Inter.
248	Gracewood	55	20	6	22	26.2	20.9	Poor
249	Gracewood	49	19	0	20	21.5	16.7	Inter.
250	Gracewood	56	20	0	32	15.3	17.2	Inter.
251	Gracewood	65	21	1	51	26.7	28.9	Poor
252	Gracewood	48	20	7	30	28.6	24.7	Poor
253	Gracewood	69	22	0	1	19.2	9.9	Good
254	Gracewood	74	21	0	0	10.4	5.2	Good
255	Gracewood	34	17	0	15	14.6	11.8	Inter.
261	Bellevue	25	50	0	4	17.7	10.1	Inter.
262	Bellevue	30	58	0	1	15.2	7.9	Good
263	Bellevue	27	56	0	11	9.2	7.9	Good
264	Bellevue	28	58	0	11	12.4	9.5	Good
265	Bellevue	27	54	0	10	15.0	10.5	Inter.
266	Bellevue	25	62	0	3	13.4	7.6	Good
267	Bellevue	28	54	0	1	9.4	5.0	Good
268	Bellevue	28	60	0	14	10.6	9.5	Good
269	Bellevue	32	66	0	6	10.9	7.2	Good
270	Bellevue	24	60	0	4	13.0	7.7	Good
271	Bellevue	27	64	0	11	12.8	9.7	Good
272	Bellevue	26	60	1	4	16.0	9.4	Good
273	Bellevue	26	62	0	18	24.6	17.7	Inter.
274	Bellevue	26	54	2	3	47.5	25.1	Poor
275	Bellevue	24	60	2	9	15.5	10.8	Inter.
276	Bellevue	30	58	2	4	25.3	14.3	Inter.
277	Bellevue	29	64	0	16	27.5	18.5	Inter.
278	Bellevue	29	62	1	14	18.4	13.6	Inter.
279	Bellevue	22	61	2	8	13.3	9.5	Good
280	Bellevue	26	54	0	14	19.0	13.7	Inter.
281	Bellevue	29	64	5	26	22.5	20.1	Poor
282	Bellevue	28	62	0	13	26.3	17.0	Inter.
283	Bellevue	28	54	9	27	29.8	24.8	Poor
284	Bellevue	29	65	12	29	31.5	26.8	Poor
285	Bellevue	26	58	0	5	34.1	18.6	Inter.
286	Bellevue	21	58	1	20	32.4	22.4	Poor
287	Bellevue	24	64	5	39	47.5	36.4	Poor
288	Bellevue	21	52	5	34	64.9	43.7	Poor
289	Bellevue	25	60	1	17	38.9	24.7	Poor
290	Bellevue	28	58	6	14	29.3	20.1	Poor

were collected at heights of 1.4, 7.6, and 10.7 m. From the main leader of each tree, five years of twig growth (2002 to 2006) were measured from five of the canopy branches subjected to full light.

On 18 September 2007, 30 ash trees along Bellevue were selected for evaluation. Measurements and cookies were collected using the same methods as performed on the Gracewood trees but with the following modifications: 1) Fish-eye hemispherical and multiple telephoto images (3264 x 2448 pixels) were taken with the telephoto images focused on representative portions of the canopy; 2) exit holes were counted between 1.2 and 1.8 m on only the south and west faces of the trees; and 3) twig growth for seven years was measured from five branches on the main leader. These modifications were influenced by observations and data analysis of the previous year's Gracewood trees.

Tree Samples Analysis

Each cookie was dated to determine the age of the sample, and the cookies were prepared for further dendro analysis by planing and sanding with 80 to 250 grit sandpaper. Ring widths, including early and latewood, were calculated using Windendro software (Regent Instruments Inc. 2005), which uses scanned images of the cookie to measure the rings. The oldest trees were cross-dated among each other with the COFECHA software (Holmes 2002) to standardize dates among rings. Using increases in basal area measurements, the percent change in growth was calculated to represent the last 15 years of radial expansion.

Average ring-widths across two transects for each section (cookie) were calculated. Transects were positioned to avoid areas of compression wood or to compensate for the variation between compression wood and non-compression wood if it could not be avoided. From ring widths, basal area increments in cm^2 were calculated to examine yearly growth. Basal area increments have been found to be an indicator of wood production for any given year (Visser 1995).

Weather data collected from the Toledo Express Airport were obtained from the National Climatic Data Center and used to evaluate growing conditions for the period 1990-2007. Monthly precipitation and temperature for the 17 months prior to September 30 for each of 15 annual rings were compiled and statistically compared to the ring widths. It should be noted that urban street trees, as opposed to forest-grown trees, may have additional confounding factors related to growth due to variations in management and artificially impacted growing conditions among trees within the tree lawn.

Hemispherical photographs were processed for both streets to calculate the site openness and percent canopy light transmission using the Gap Light Analyzer 2.0 software (Frazer and others 1999). The imaging software was used to extract canopy structure and gap light transmission indices from true-color fisheye photographs. Best results are obtained on cloud free days when the sun is not directly overhead. Movement of twigs and leaves from wind should be minimized for best quality images. These conditions were mostly present during our field sampling days.

From each image, a total of five subsamples were collected to assess overall light transmission through the tree canopy: three samples with a radius of 65 pixels and two samples with a radius of 180 pixels. Sample data were averaged to obtain percent light transmission for each tree. In 2007, telephoto images were also collected to compare against the hemispherical method. The telephoto images were processed by sampling three sub-samples, one with a radius of 1000 pixels (centered) and two with a radius of 1232 pixels (left and right sides).

The locations of each tree were geographically placed into a GIS so that the percentage of canopy light transmission, DBH, and index classes could be spatially visualized and assessed (Fig. 1 and 2). The year of first attack, as estimated from our samples, was also used to help develop the classification scheme.

Development of Ash Tree Health Index

To develop our non-destructive rating of tree health, values of three symptoms (canopy light transmission, epicormic shoots, and exit holes) related to EAB infestations were used to formulate the Ash Tree Health Index (ATHI). The values used to derive the ATHI were:

((Percent Light Transmission * 0.5) + (# Epicormic Shoots * 0.3) + (# Exit Holes * 0.2)).

For example, a tree with 50 percent light transmission, 30 epicormic shoots, and five exit holes would have a ATHI value of [(50 * 0.5) + (30 * 0.3) + (5 * 0.2)], or 35 with greater values representing declining health. Because EAB tends to colonize in the upper canopy and our sampling was 1.2 – 1.8 m above the ground for ease and safety in sampling, exit holes were weighted less (20 percent of weight) in the ATHI. Exit holes do, however, serve well as a confirmation of EAB infestation. Epicormic branching is also a later sign of infestation and was weighted at 30 percent. Percent light transmission was given the greatest weight (50 percent) because EAB tends to attack in the upper crown first.

Statistical Analysis

A multivariate correlation analysis was performed using the CORR procedure with SAS/STAT® software (SAS Institute Inc., 2003) on canopy transmission, epicormic branching, twig extension growth for each year, height, DBH, and total exit holes. A nonlinear analysis procedure (NLIN) was used to analyze basal area increment (BAI) by year. A RandomForest regression tree analysis was performed (using the RandomForest algorithm in R (Prasad and others 2006)) on the total number of exit holes, epicormic shoots, and canopy transmission against the ATHI value.

RESULTS AND DISCUSSION

Classification Index

The ATHI was calculated for both the Gracewood and Bellevue trees. Thresholds for three classes were set by modifying natural break points among the index values. Using the break points of < 10=good, 10 – 20=intermediate, and > 20=poor, the index classed 13 trees as good, 13 trees as intermediate, and 19 as poor. When ATHI scores are used to classify the health of the sampled trees (Table 1), the process can be repeated objectively to compare tree health among individual trees or monitor a single tree over time.

The regression tree analysis (Fig. 3) correctly places 37 of the 45 (82 percent) trees into one of the three ATHI classes where light transmission is the dependent variable and epicormics shoots and exit holes are independent. This further indicates the potential of the ATHI to rank ash tree health.

Trends in Tree Growth and Vigor

Tree Ring Analyses. The Gracewood trees ranged from 23 to 42 years old at DBH with an average age of 37 ± two years, but most were between 38 and 41 years. Little variation was observed in BAI before 2003, but a decline in growth was present during the last one to two years in most trees (Fig. 4). The nonlinear analysis showed positive growth in Gracewood trees until 2005 in good and intermediate trees while poor trees rapidly declined beginning in 2004. The Bellevue trees, some more than 45 years old, did not show increasing growth before the decline, and in good and intermediate trees, the decline was rapid after 2004 at DBH (Fig. 4). Due to the greater age and size in BAI of the trees on Bellevue as compared to Gracewood, BAI would not be expected to show such a regular increase. Rather, measured growth was highly variable in these trees over the sampled years (Fig. 4).

All trees classified by the ATHI as having intermediate (10-20) or poor (>20) health had a reduction in growth beginning in the 2004 growing season. Exit holes from the cookies indicated that the earliest known attacks occurred during the 2004 growing season, but because we evaluated only the small amount of tissue represented by the cookies and because EAB normally attacks the upper canopy first, we expect that initial infestation occurred prior to 2004.

The ATHI classes are generally related to the year of initial growth decline. For poor trees, decline started in 2004, for intermediate trees, 2005, and for good trees, 2006 (Fig. 5). After these initial years, all trees suffered a progressive decrease in ring production. In the year prior to this decrease, ring width was generally greater (Fig. 5).

Twig extension growth. Extension measurements for five years of growth on Gracewood and seven years on Bellevue trees confirmed the decrease in production after EAB attacks. For Gracewood trees after 2003, twig extension growth was progressively lower ($R^2 = 0.92$, $p = 0.017$) from good to poor trees, and growth rates were generally lower in later years (Fig. 6a). Percent change in branch growth for the Gracewood trees was negative from 2003-2006 in poor trees, from 2004-2006 in intermediate trees and in 2004 and 2006 in good trees (Fig. 7a). The Bellevue trees, with a seven-year record, showed a general decline in branch extension beginning in 2004 ($R^2 = 0.90$, $p = 0.003$) (Fig. 7b). All trees thus showed substantial decline in both ring and twig growth by 2006, with EAB as the most likely cause of the decline.

Light Transmission. For the 45 trees from Gracewood and Bellevue examined for light transmission with digital hemispherical photographs, the tree canopies occupied ~30 percent of the hemispherical image, and the total sampled area was only seven percent of the space that the canopy occupied. The percentage of open sky seen from beneath the trees ranged from nearly seven percent to 36 percent light transmission. However, telephoto images taken on the Bellevue trees in 2007 offered more (~60 percent) of the tree's canopy for processing, resulting in 83 percent of the image processed including 41 percent of the image which was processed more than once. The values of canopy transmission ranged from nine percent to 65 percent for the Bellevue trees.

These statistics suggest that the telephoto images result in a more representative value for canopy light transmission through

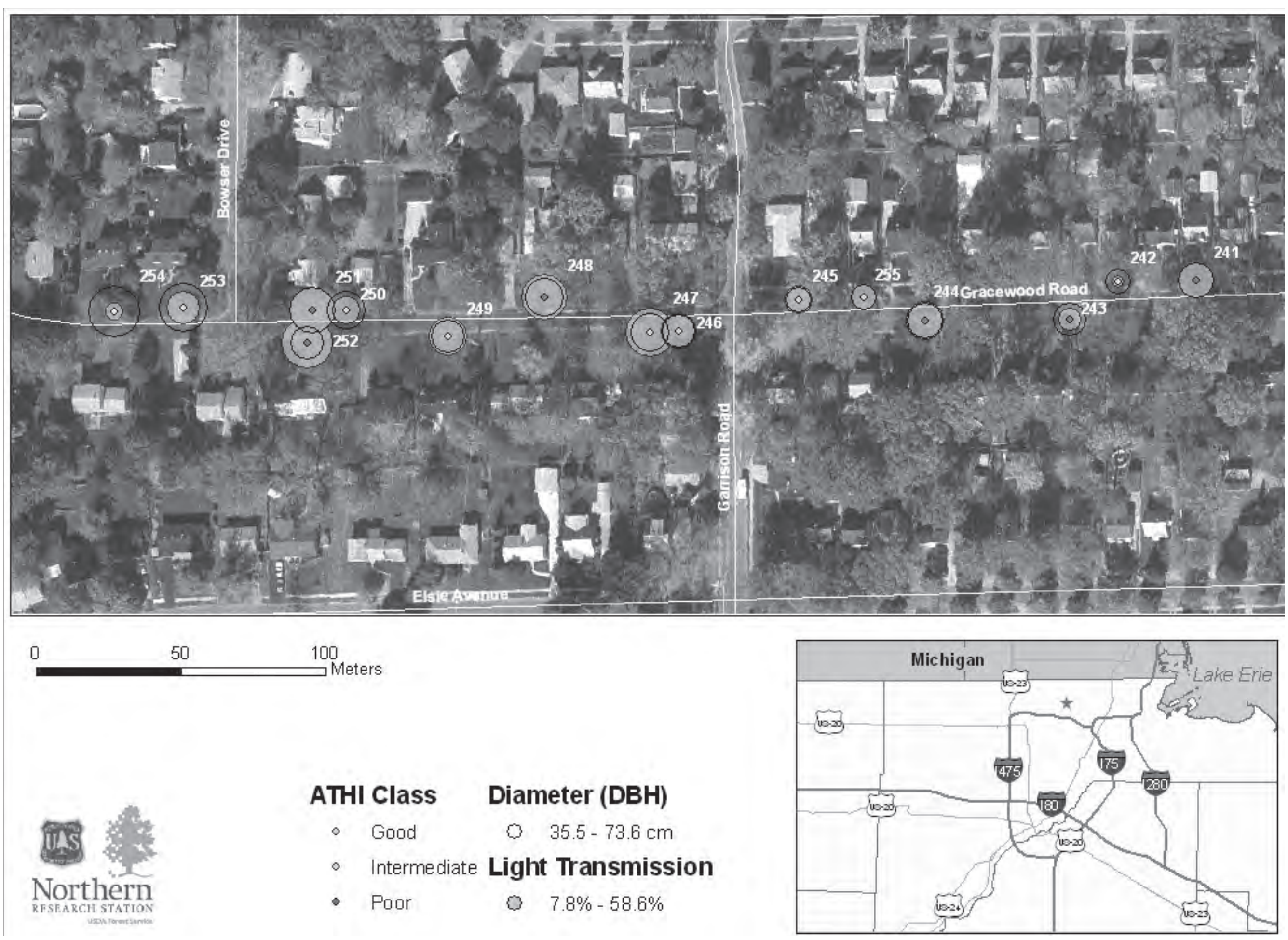

FIGURE 1. Gracewood Road and the ash trees used in the study. Values of light transmission and diameters are displayed proportionally to each tree and do not represent the exact area of canopy openness or tree size. Larger circles for light transmission signify the amount of light that penetrates the canopy. Also presented are the ATHI classes for each tree. The inset map denotes (*) the location of the street within Toledo, OH.

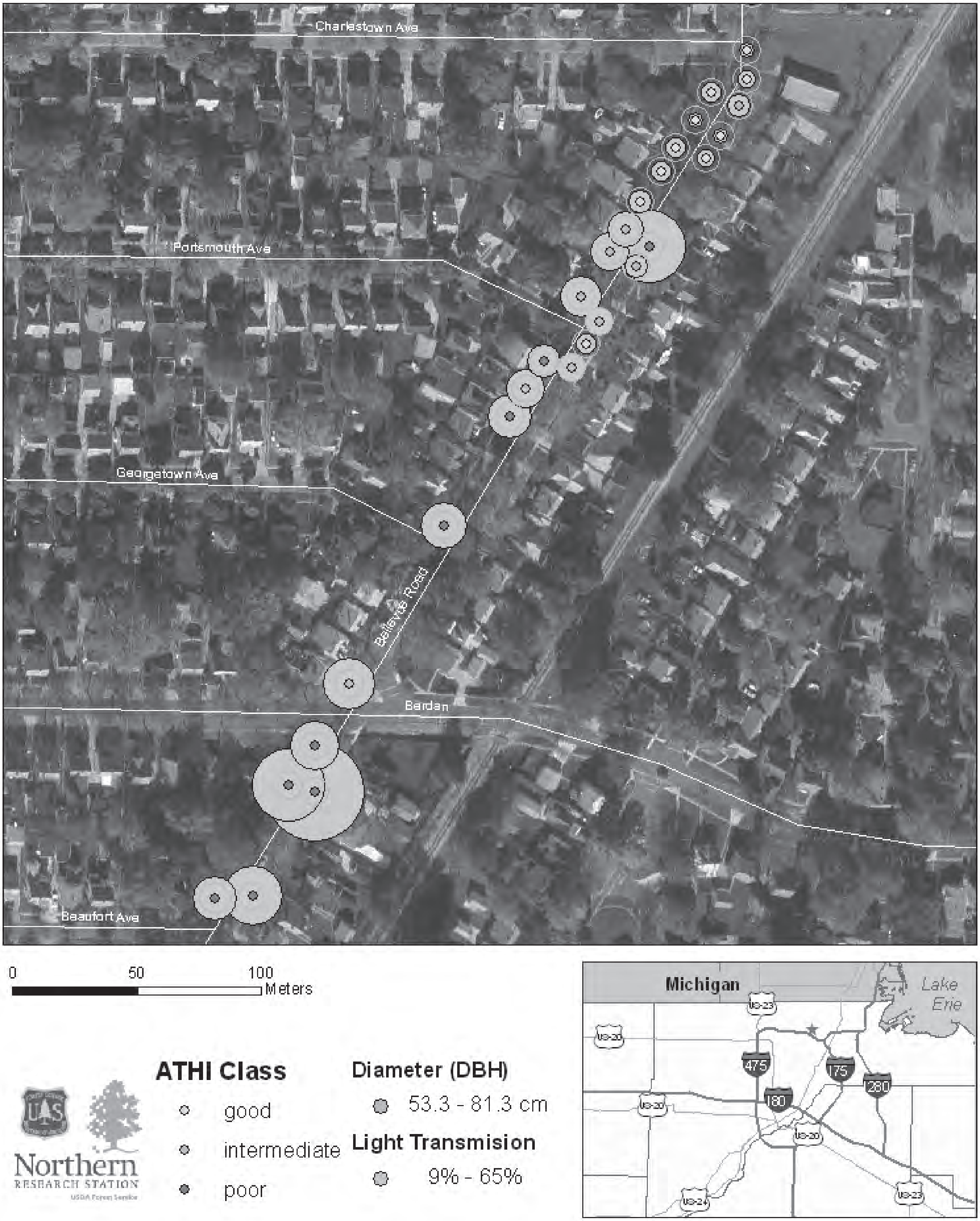

Figure 2. Bellevue Road and the 30 ash trees used to calibrate the ATHI. More poor trees were found near the southern end of the street (near Interstate 475), while more good trees were found at the northern end. The inset map denotes (*) the location of the street within Toledo, OH.

single trees as compared to the hemispherical photographs. Light transmission from Gracewood, as obtained via hemispherical photographs were more correlated to the number of D-shaped exit holes ($R^2 = 0.56$, $p = 0.01$) than the telephoto-obtained values from Bellevue ($R^2 = 0.47$, $p = <0.001$). However, the light transmission values from Bellevue telephoto images were more correlated to epicormic shoots ($R^2 = 0.61$, $p = <0.001$) than the Gracewood values ($R^2 = 0.23$, $p = 0.2$). These differences can be attributed to the overall severity of damage to the trees on the two streets. Due to the nature of the software, samples need to be free of surrounding sky that skews the results for single tree analysis. Therefore, we advocate that telephoto rather than hemispherical images be used to assess canopy transmission because telephoto lenses can isolate representative areas of a tree's canopy against open sky and simplify processing.

Epicormic branching. As a response to EAB attacks, trees produce epicormic shoots (Cappaert and others 2005, Poland and McCullough 2006, McCullough 2007), and we used the number of epicormic shoots to help classify its health condition. Our trees had a range of zero to 87 shoots counted from the bottom 4.9 m of the boles. Trees in good condition produced very few epicormic shoots (mean of five) compared to those in intermediate (15) and poor (35) conditions (Table1). The abundance of epicormic shoots may be linked to the additional light allowed to pass through the canopy, restrictions to flow in phloem, or a disruption in secondary metabolites caused by the insect. Though mechanisms are still not well known, some studies suggest that light lower in the crown is a factor in the production of epicormic shoots (Trimble and Seegrist 1973; Godman 1992; Nicolini and others 2001).

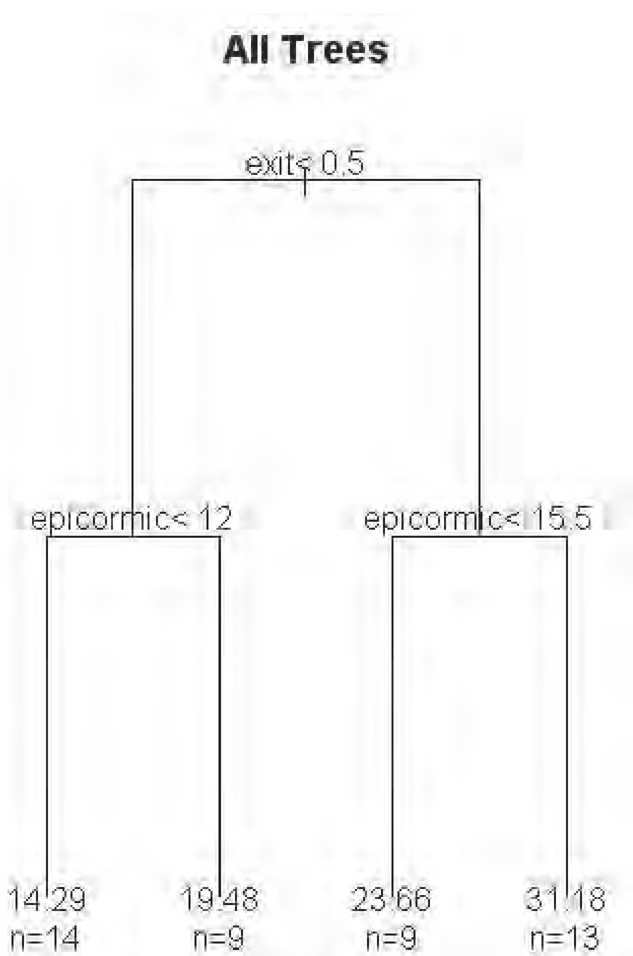

Figure 3. A regression tree analysis utilizing the random forest algorithm correctly placed 80 percent of the trees into one of three ATHI classes. The mean value for ATHI is reported above the sample value; tree health decreases from left to right.

Exit holes. D-shaped exit holes, which can confirm the presence of EAB, are an important factor in our classification of a tree's health; however, low populations of EAB will most often attack the tree's canopy before visual signs become present near the ground (Cappaert and others 2005). Of the 45 trees, 23 were found to have no exit holes in the sampling area at DBH, but evidence of stress was present in other parts of the tree. In general, the good trees had the fewest (mean of <1), followed by intermediate (1) and poor (5) number of exit holes (Table 1). The south-facing side of seven Gracewood trees ranging from intermediate (two trees) to poor (five trees) had the most exit holes based on the randomly sampled data. Since we observed a greater number of exit holes on the south and west faces of the boles, we modified our sampling method for Bellevue to only include those sides. A visual check confirmed that most trees did not have exit holes on the north and east faces of the sampling area. The extra warming and higher incidence of light levels on the south-facing aspects of the tree boles appear to promote larval development on the south side of the tree, also found by Wei and others (2007).

Pearson correlation analysis revealed that each of the three variables of the ATHI (light transmission, epicormic branching, exit holes) were positively correlated to each other, especially on the Bellevue trees. These relationships indicate that these variables are appropriate for the classification scheme.

Weather. The 17-month (May of previous year to September of the current year) precipitation profile was not found to be statistically related to our BAI or twig extension measures of growth. The year 2001 had the greatest rainfall deficit of the 2000-2006 period. In that year, precipitation was 21.4 cm above normal for the first six months of the 17-month period and then dropped to 9.9 cm below normal during the last 11 months. Precipitation during the 17-month period for 2003 was also below normal, while in 2006, rainfall was 14.6 cm above normal. How much human interaction (irrigation, pruning, mulching, and fertilization) impacted growth on these street trees remains unclear.

CONCLUSIONS

Both traps and visual surveys are needed to determine the distribution of EAB infestation within urban settings. However, the former method only predicts the presence of an infestation, not the tree's state of vigor. Indexing the symptoms can provide quantitative values to gauge a tree's health, as opposed to a simple subjective visual evaluation. This could lead to more accurate management recommendations for EAB-infested trees including when to recommend tree removal, replacement, or pesticide usage.

Even though the canopy symptoms of EAB and ash yellows are similar, specific symptoms such as increased number of woodpecker holes, D-shaped exit holes, larval galleries, or the presence of EAB adults or larvae will confirm EAB rather than ash yellows. We anticipate that ATHI would be useful in monitoring the progression of EAB among ash trees. The ATHI and thresholds for each health condition were formulated from data collected from the Gracewood and Bellevue trees that were known to be infested by the EAB. We do not expect that the absolute ATHI score shown here would be applicable everywhere, but that adjustments can and should be made to the index according to varying conditions at the site, as well as slight variations in the lab and field methods. However, a quantitative assessment of the declining health of the urban street and park trees can help determine the stage of the EAB infestation and more precisely identify management options.

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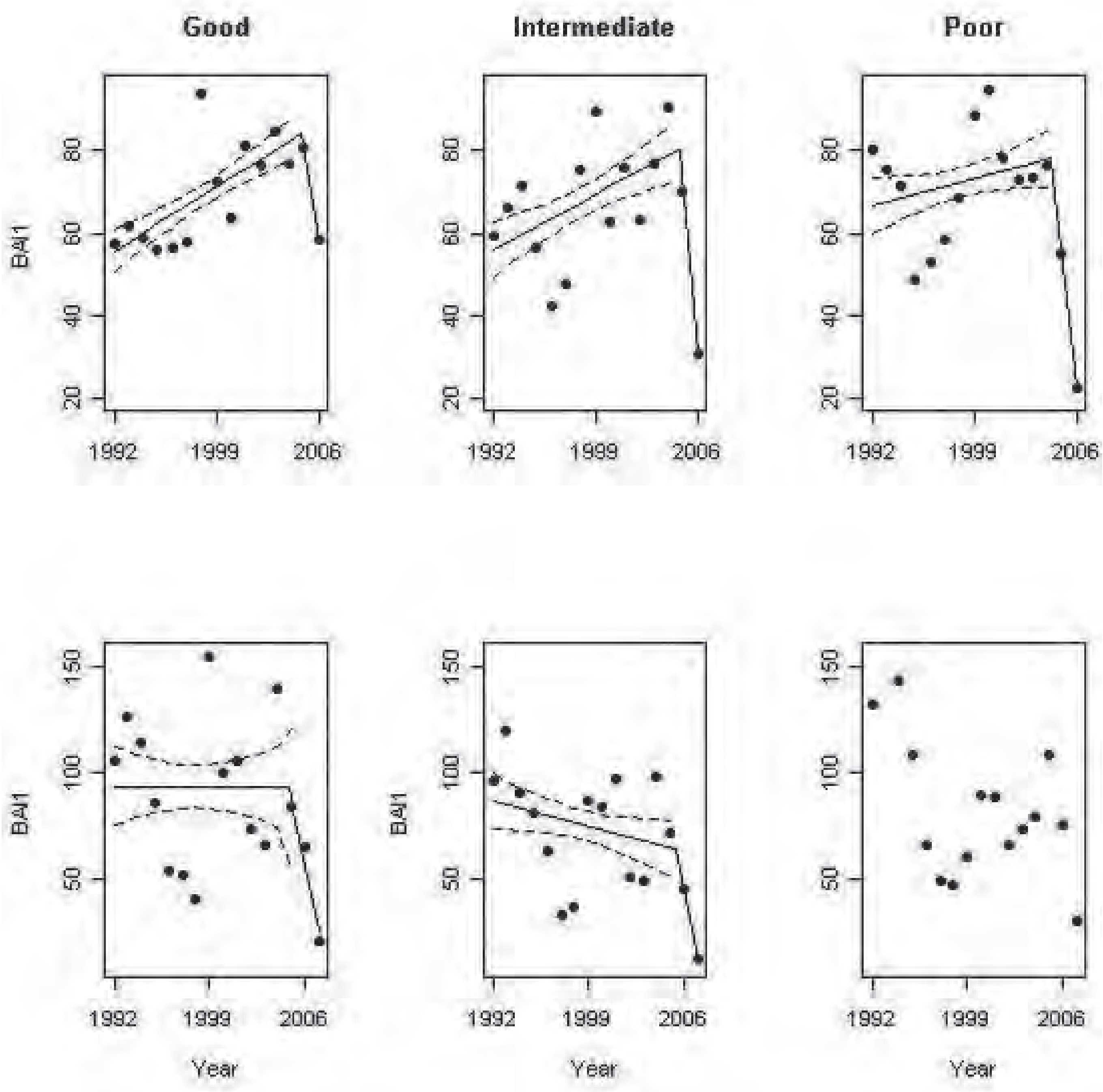

Figure 4. Average basal area increments during the last 15 years of growth (1992 – 2006) for trees classified as good, intermediate, or poor for Gracewood (above) and for the past 16 years (1992-2007) for Bellevue (below) measured from the sections at 1.4 m. A rapid crash in ring growth occurs, especially on the intermediate and poor trees following the earliest year of known attack, 2004. The standard deviation is shown as dashed lines.

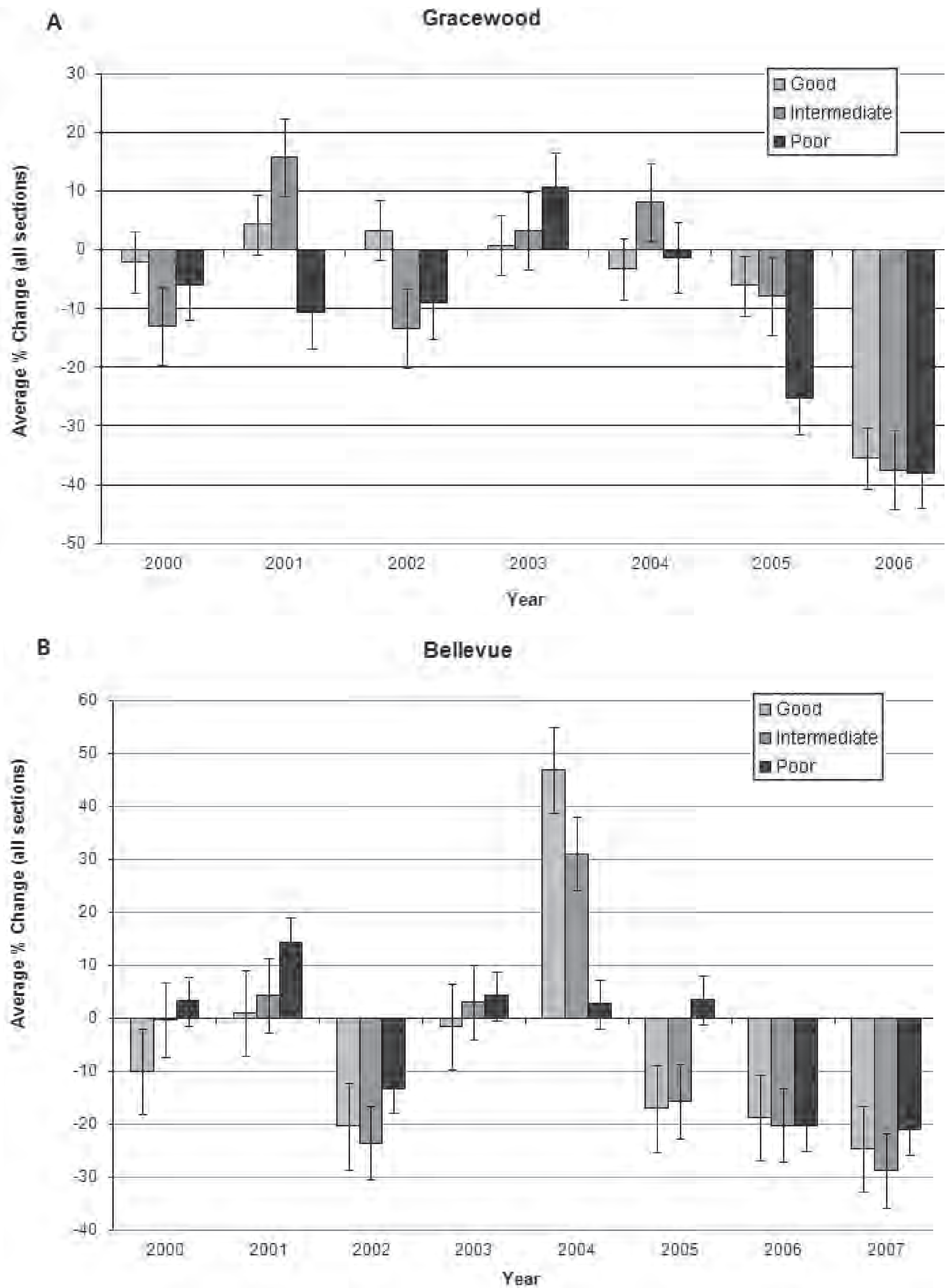

FIGURE 5. Average ring widths for each class were used to calculate the percent of change of growth between years. Note the early decline in ring production in 2004 (Gracewood) and 2005 (Bellevue) were preceded by an increase. Error bars show the mean standard error.

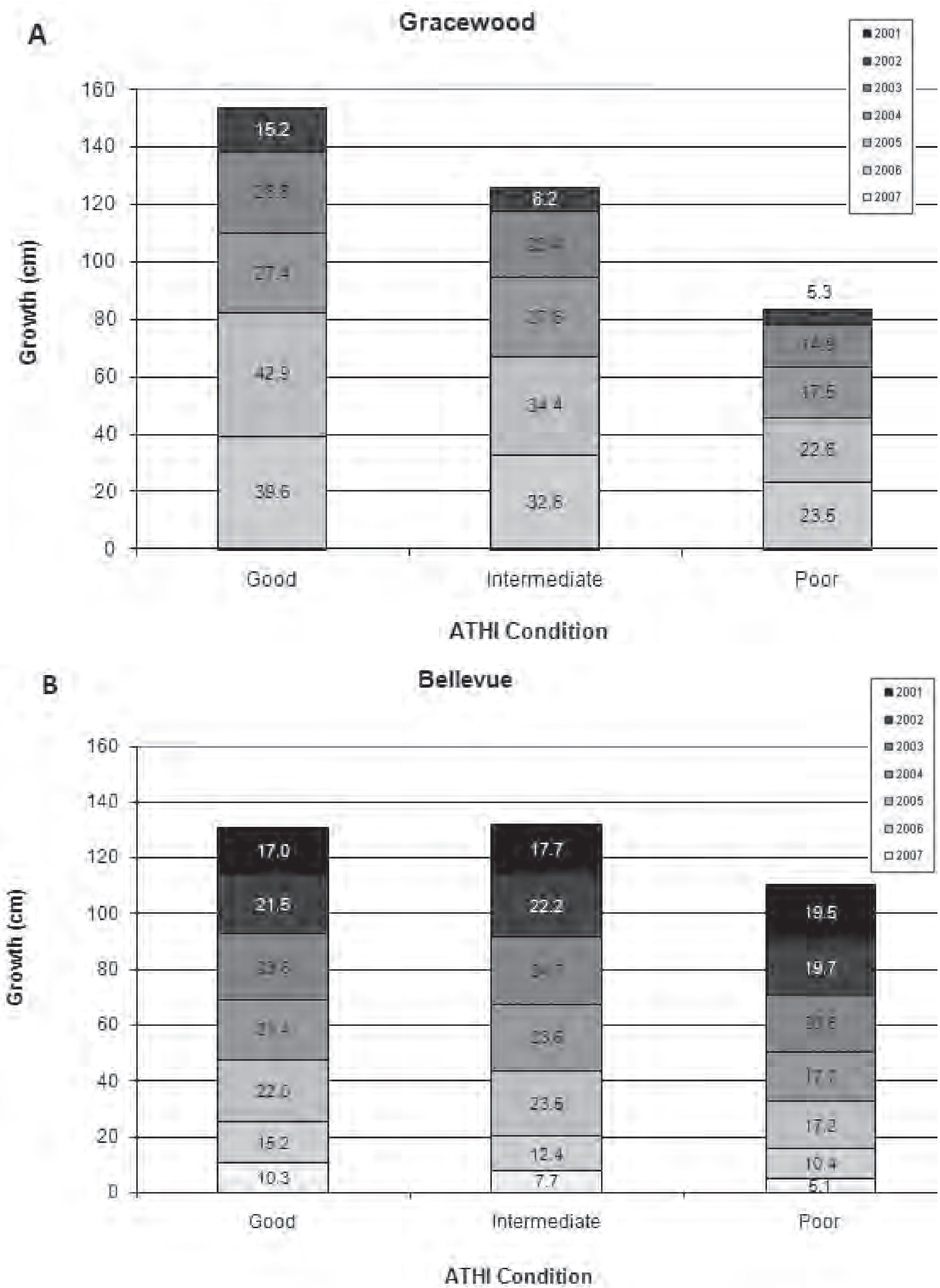

FIGURE 6. The average five (Gracewood) and seven (Bellevue) years of twig extension growth. Values based on the total averages for each tree calculated from measurements of five branches on the main lead.

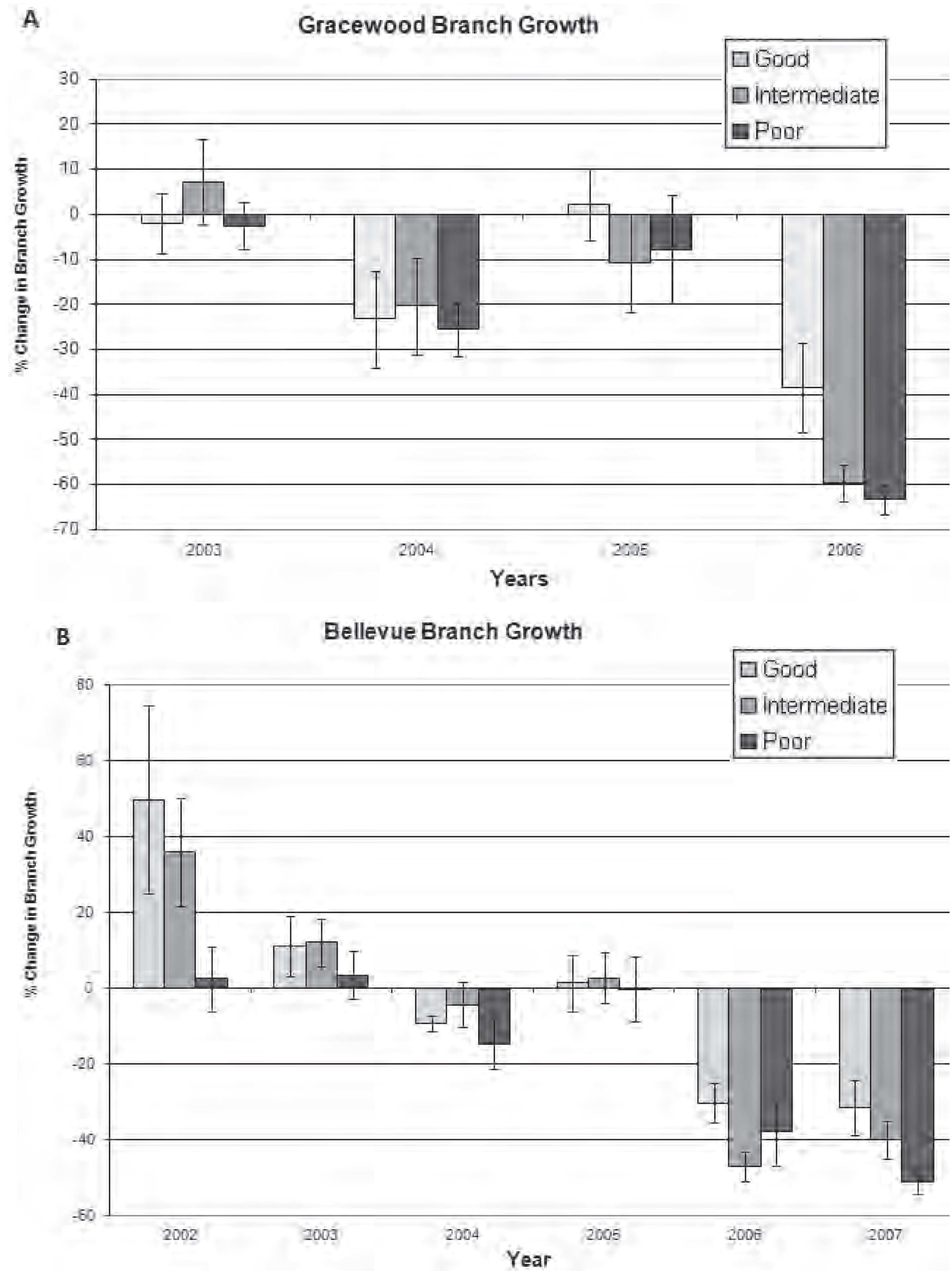

FIGURE 7. Average percent change in twig extension growth for five (Gracewood) and seven (Bellevue) years. Error bars represent the mean standard error.

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