RESEARCH NOTE

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Patterns of Coarse Woody Debris in Hardwood Forests across a Chronosequence of Ash Mortality Due to the Emerald Ash Borer (*Agrilus planipennis*)

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ABSTRACT: The invasive emerald ash borer (*Agrilus planipennis*) (EAB) is causing widespread ash (*Fraxinus* spp.) mortality in 25 U.S. states and two Canadian provinces. We investigated the impact of EAB on coarse woody debris (CWD) volume across 24 sites in western and central Ohio, USA, representing a chronosequence of ash mortality, quantified by the year ash mortality reached 25% (Year25%Dead). CWD volume averaged 60.36 m^3/ha, and was positively associated with total (live plus dead) ash basal area (BA), but was not greater in sites where ash death occurred earlier. For the volume of CWD in the first, least-rotted, decay class, stepwise regression revealed that both ash BA and Year25%Dead were significant predictors; sites with more ash BA and where ash mortality had occurred earlier had more class 1 CWD. Additionally, class 1 CWD in those early mortality sites was primarily (87%) ash, compared to 40% ash in sites with more recent ash mortality. This large influx of CWD, particularly ash CWD, combined with future inputs from ash that are still standing, will elevate CWD volume in the near future, especially in sites with greater ash basal area.

Index terms: Agrilus planipennis, eastern deciduous forest, forest pest, *Fraxinus*, Ohio

INTRODUCTION

Emerald ash borer (EAB), *Agrilus planipennis* Fairmaire, has established in 25 U.S. states and two Canadian provinces as of 2016 (http://www.emeraldashborer.info/), following its first detection near Detroit, Michigan, in 2002 (Cappaert et al. 2005). EAB kills ash (*Fraxinus* spp.) trees about 2–4 years after initial infestation (Herms and McCullough 2014). Ash comprises about 2.5% of aboveground forest carbon in the continental U.S., and >20,000,000 Mg C in Ohio (Flower et al. 2012). Ash death due to EAB is expected to cause a large flux of coarse woody debris (CWD), downed woody materials with diameter ≥7.5 cm and length >1 m. CWD comprises 4%–7% of aboveground carbon in U.S. forests, but varies among forests due to different input rates and different decay rates (Rubino and McCarthy 2003; Domke et al. 2013), as well as natural and anthropogenic disturbances (Webster and Jenkins 2005; Russell et al. 2015). The influx and subsequent decomposition of ash CWD will impact carbon fluxes (Russell et al. 2015), fungi (Lonsdale et al. 2008), plants (Jenkins et al. 2004), animals (Harmon et al. 1986), nutrient availability (Idol et al. 2001; Hafner and Groffman 2005), change surface runoff and soil erosion (He et al. 2012), and disrupt stream flow (Harmon et al. 1986).

The purpose of this study was to assess how time since EAB-caused ash mortality affects total CWD in relatively undisturbed areas of deciduous forest in western and central Ohio. We used a chronosequence approach, where sites varied in number of years that had passed since EAB-caused ash mortality was manifest. Further, we investigated how ash basal area (BA) influences these patterns. Additionally, we sought to provide valuable baseline data for future studies of EAB impacts on ecosystem processes.

METHODS

Measurements were made in 24 forested sites (Table 1) with relatively little recent anthropogenic disturbance located throughout western and central Ohio. The sites were a subset of sites established by the US Forest Service to study impacts of EAB across a range of habitat types and ash densities (Knight et al. 2013). Most stands were secondary forest with minimal management. Nested within each site were three circular 400 m^2 plots located away from forest edges or trails, spaced >50 m apart. Each plot included ≥2 ash trees ≥10 cm diameter at breast height (dbh). Sites represent a gradient of time (1–9 years) since EAB infestation was first documented by detection of characteristic D-shaped exit holes on dying ash or trapping of EAB adult beetles.

From June to August 2013, we measured length and diameter at each end of each piece of CWD in each plot; stumps and standing CWD were ignored (Woodall and Williams 2005). Only CWD touching the ground for over 1 m and with diameter ≥7.5 cm was measured. If part of the piece had a diameter <7.5 cm, measurements were taken only at parts where the diameter was ≥7.5 cm. If the piece was partially out of

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Table 1. Study sites in western and central Ohio with map coordinates, 2012 total tree (≥10 cm dbh) and *Fraxinus* tree basal area (BA) (m^2/ha), first year when ≥25% of *Fraxinus* (≥10 cm) were dead, percentage of *Fraxinus* that had died by 2014, and total and decay class 1 coarse woody debris (CWD) volumes (m^3/ha). Note that all parameters were calculated for the study plots, not for entire stands, and plots were located to include large ash trees. *Fraxinus* trees recently killed by EAB were included in BA calculations.

Site	Lat.	Long.	Tree BA	*Fraxinus* BA	Year 25% dead	% dead by 2014	CWD volume	Decay class 1 CWD
Caesar Creek Gorge SNP	39.49	−84.10	28.37	13.30	2015	4%	9.71	1.03
Caesar Creek State Park 1	39.49	−84.04	30.04	6.41	2012	40%	134.08	15.83
Caesar Creek State Park 4	39.51	−84.05	45.22	16.98	2015	9%	97.67	70.44
Caesar Creek State Park 5	39.54	−84.00	42.62	11.55	2015	20%	60.63	3.06
Clifton Gorge SNP	39.79	−83.84	36.03	9.65	2015	23%	46.70	7.62
Culberson Woods SNP	39.37	−83.93	46.97	14.67	2015	21%	24.34	0.77
Dempsey Middle School	40.31	−83.08	23.10	5.86	2008	87%	1.46	0.30
Edwards Furniture	39.57	−84.26	36.80	16.41	2008	89%	124.03	86.35
Englewood Metropark	39.89	−84.28	32.09	20.08	2014	35%	30.28	1.45
Fallen Timbers 1	41.55	−83.69	41.55	15.66	2008	100%	54.12	31.70
Fallen Timbers 2	41.55	−83.69	48.10	13.74	2009	100%	41.07	13.70
Gahanna Woods SNP	40.01	−82.84	14.77	5.95	2013	65%	0.98	0.00
Germantown Metropark	39.64	−84.40	36.24	12.76	2014	36%	21.40	0.74
Glenwood Gardens	39.26	−84.49	41.63	24.90	2015	24%	102.53	45.23
Highbanks Metropark	40.15	−83.03	28.97	13.98	2007	100%	24.08	8.42
Hueston Woods SNP	39.57	−84.75	48.19	30.46	2011	43%	112.67	99.20
Maumee State Forest	41.54	−83.93	38.78	14.76	2005	100%	53.40	38.46
Oak Openings 2	41.56	−83.87	64.75	33.14	2006	100%	160.40	139.64
Oak Openings 3	41.54	−83.85	51.48	22.25	2006	100%	154.69	132.01
Pearson	41.64	−83.43	59.20	29.23	2008	100%	56.19	40.28
Seymour Woods SNP	40.23	−83.06	33.03	9.71	2009	100%	29.32	11.63
Sharon Woods Cincinnati	39.28	−84.40	34.38	15.54	2014	29%	42.09	30.53
Sharon Woods Columbus 2	40.12	−82.97	18.81	6.38	2010	64%	25.59	7.51
Stratford Ecological Center	40.25	−83.07	38.64	14.82	2009	100%	41.23	13.03

the plot, then only the material within the plot was measured.

The decay class of each piece was determined by texture, structural integrity, and appearance following Pyle and Brown (1998). Decay class 1 pieces were freshly fallen while decay class 5 wood was very spongy. CWD in the first decay class was identified to genus.

In each plot, yearly ash health surveys of trees ≥10 cm dbh (Knight et al. 2014) allowed us to determine both ash BA and annual mortality level. Ash BA was calculated from dbh of all ash (alive, standing dead, and those that fell subsequent to EAB infestation) ≥10 cm dbh. To characterize the stage of ash mortality for each stand at the time of sampling, we used the first year ≥25% of ash trees (≥10 cm dbh) were scored as dead (denoted "Year25%Dead"); this measure correlated with the year EAB was first trapped, but the latter measure was not available for every stand. Ash mortality in infested stands follows a characteristic pattern (Knight 2014) reflecting the time course of infestation and mortality from EAB. Below, we distinguish between "early mortality sites," where Year25%Dead occurred in 2010 or earlier, and "late mortality sites," where this threshold was reached in 2011 or later. This latter set includes six sites that had only 4%–24% dead by 2014, and were assigned a Year25%Dead of 2015. We also recorded for each site, the proportion of ash trees (≥10 cm dbh) that had fallen (primarily from EAB-caused mortality) by 2013.

The volume of each piece of CWD was calculated using the formula for a frustum of a cone, $V = H\varpi(R_1^2 + R_1R_2 + R_2^2)/3$ (McGee 2000; Fraver et al. 2002; Rubino and McCarthy 2003), where H is the length of the log, R_1 is the radius at one end of the log, and R_2 is the radius at the opposite end of the log. For each site, we calculated the average across the three plots of CWD volume and ash BA. Because ash BA and total tree standing BA were highly correlated (Pearson correlation coefficient of 0.73), total tree standing BA was excluded from the analysis.

To determine which site characteristics best explained CWD, a backward stepwise linear regression model was run with total CWD volume as the response variable and ash BA and Year25%Dead as the initial predictors. The Akaike's Information Criterion (AIC) was used to determine which variables were kept in the model.

A similar backward stepwise linear regression model was run using only CWD volume in the first decay class as the response with the same predictors as above. In both models, CWD volume was log-transformed.

The stepAIC function within the MASS package of R version 3.2.1 was used for the stepwise regressions. We used linear regression to describe the relationship between proportion of ash that had fallen and Year25%Dead.

RESULTS

Ash BA ranged from 6 to 33 m^2/ha among sites (mean 15.72 m^2/ha), corresponding to 21%–63% of total BA (Table 1). EAB-caused ash mortality first reached 25% in 2005–2009 for sites closest to the initial introduction location in southeastern Michigan and later for more distant sites (Figure 1).

Across sites, CWD volume averaged 60.36 m^3/ha. Sites in central Ohio tended to have the least CWD, while two sites in northwestern and one site in southwestern Ohio had the most CWD volume (Table 1). Among the 24 sites, CWD volume was best explained by ash BA (F =11.07, df = 1, 22, P = 0.0031); plots with more ash BA had more CWD volume. Year25%Dead was not a significant predictor of CWD.

Volumes of CWD in each decay class decreased monotonically in early mortality sites, whereas volume of CWD peaked at the second decay class in recent mortality sites (Figure 2). In early mortality sites, where many ash had been dead for three or more years, the volume of CWD in the first, least-rotted, decay class was more than double that in recent mortality sites.

Ash comprised 87.2% of decay class 1 CWD in early mortality sites, compared to 40.5% in recent mortality sites. The volume of decay class 1 CWD was significantly predicted by ash BA (F = 14.74, df = 1, 22, P = 0.0002) and Year25%Dead (F = 4.71, df = 1, 22, P = 0.0417) (multiple regression R^2 = 0.54). Sites with more ash BA and earlier ash mortality had more CWD in the first decay class (Figure 3). The proportion of ash that had fallen by 2013 was significantly correlated with Year25%Dead (r = 0.78, P < 0.001).

DISCUSSION

Total CWD volume did not show a pattern across our 24-site chronosequence, spanning a range of nine years following EAB-caused ash mortality, but there was a pulse of decay class 1 CWD. This decay class corresponds to recently downed wood, as most CWD pieces advance to decay class 2 within five years (Russell et al. 2013). In fact, in sites where ≥25% of the large ash had died ≥3 years earlier, class 1 CWD was more than double that in sites with more recent ash mortality. This greater volume of recently downed wood was the direct result of EAB infestation, as ash comprised nearly 90% of class 1 CWD in these sites.

The lack of a relationship between total CWD and year of ash mortality may be due to the large variability of CWD in decay classes 2–5 across sites that varied in stand age and species composition. In addition, sites have not yet experienced the complete pulse of CWD. In sites with the earliest mortality (25% in 2005–2006, increasing to ≥90% by 2008–2009), only 60%–80% of dead ash had fallen by 2013; more dead ash falling will further elevate CWD. For comparison, Harmon et al. (1986) found that CWD mass peaked 12 years after fire in a spruce-fir forest.

Both total and class 1 CWD were positively associated with ash BA across the 24 sites. This suggests that CWD impacts from EAB-caused mortality will be greatest in sites with abundant ash and that sites with low ash BA may experience little change in CWD dynamics. Our finding that forests with a larger component of ash have a larger amount of CWD could be due to differences among forest sites in successional stage, differences among forest tree species in rates of shedding of lower limbs or mortality rates before EAB infestation, or early losses of dead limbs from EAB-infested ash that are still alive. Results from our study suggest that the pulse of CWD from EAB-caused ash mortality may play out over many decades after initial EAB infestation. The initial influx of CWD into decay class 1 likely peaks about five years after the majority of ash die, as 80% of trees fall within five years of death (Knight 2014). Because ash decays quicker than other hardwoods (Russell et al. 2013), we expect that this pulse of downed wood will advance quickly to higher decay classes. The CWD pulse and its effects will be especially pronounced in sites with a high ash BA, yet may be within the range of natural CWD dynamics in sites with low ash BA. Since our plots were chosen to include ash, stand-level effects will be more modest.

Animal communities will be impacted by this influx of CWD and its subsequent decay. Ulyshen et al. (2011) found that after dead ash fall, arthropods and exotic earthworms occur at higher densities near decay class 1 ash boles than 1–3 m away. Across sites in Michigan, ground beetle density was negatively correlated with ash mortality, but increased over time (Gandhi et al. 2014). Ash CWD may also promote tree recruitment in sites with high deer browse pressure, as seedlings were associated with large CWD piles (Brian Hoven pers. obs.).

The consequences of the large influx of CWD following EAB include changes to forest floor microhabitats and nutrient availability; N, P, and S are immobilized in the early stages of CWD decomposition, while Ca, K, and Mg are mineralized (Idol et al. 2001). These changes, in addition to more canopy gaps created by dying ash, could facilitate invasive plant colonization (Davis et al. 2000). Additionally, as ash die, other trees may become more vulnerable to wind, further adding to the pool of CWD on the forest floor (Sturtevant et al. 1997). Recovery of CWD to pre-disturbance levels can be very slow, occurring on a time scale of hundreds of years in most forest types (Fraver et al. 2002).

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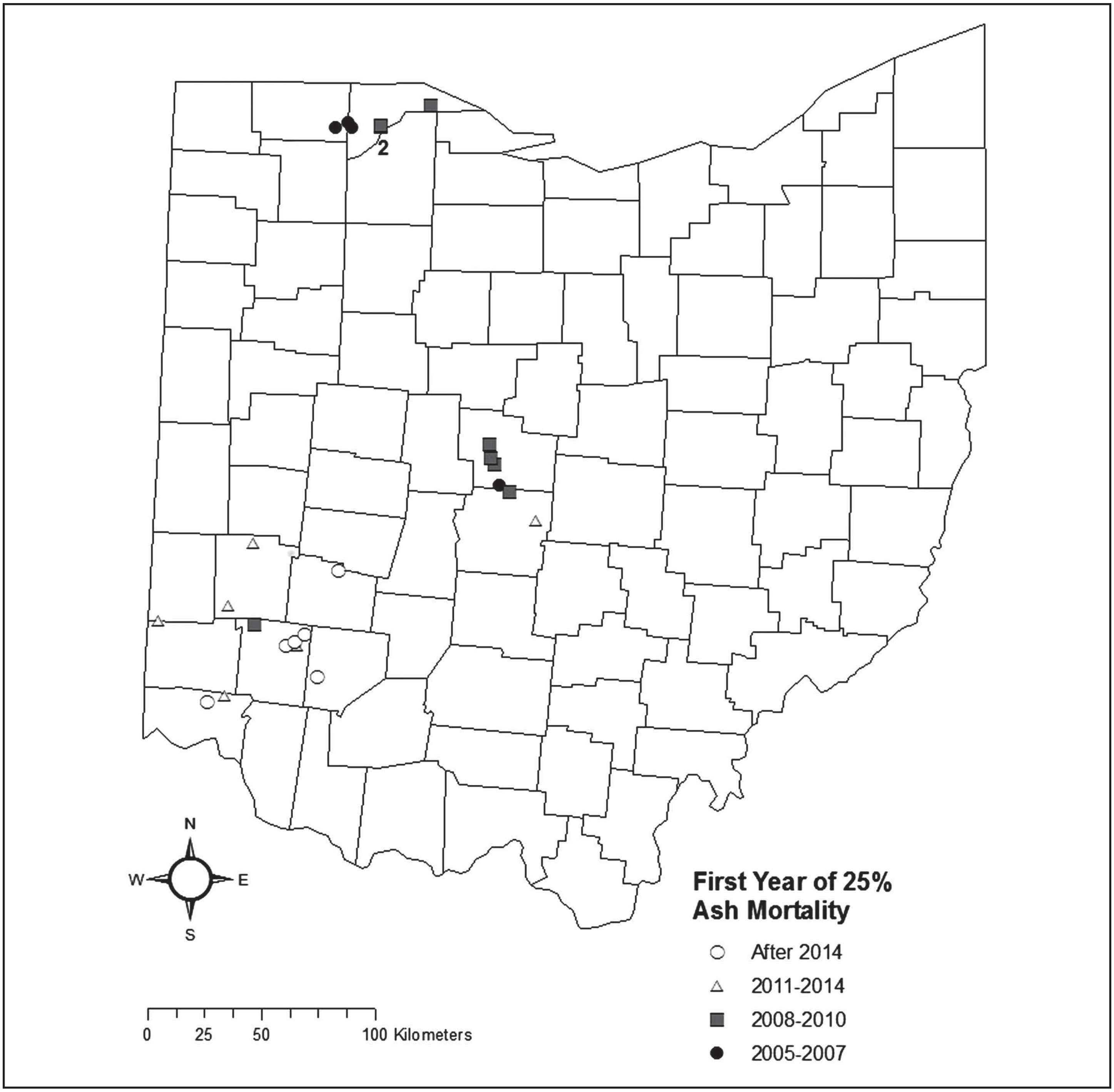

Figure 1. Map showing the first year that ≥25% of *Fraxinus* (≥10 cm dbh) were dead in each of the 24 sites. The "2" indicates two sites in close proximity that reached 25% dead in the same three-year interval.

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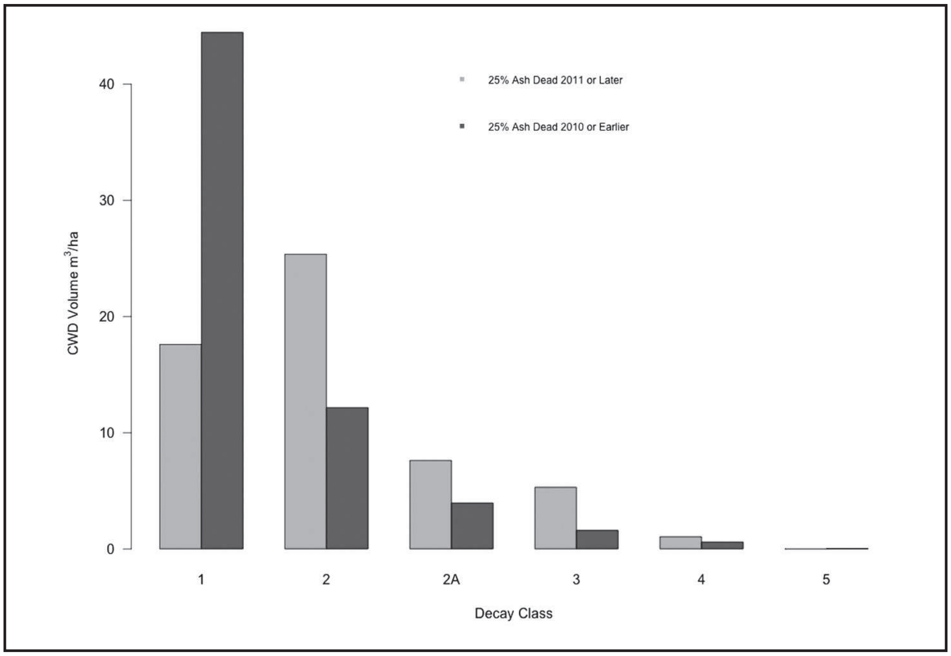

Figure 2. Distribution of coarse woody debris (CWD) volume across six decay classes for sites with early *Fraxinus* mortality (≥25% dead by 2010 or earlier) compared to sites with recent *Fraxinus* mortality (≥25% dead by 2011 or later).

on woody plant community responses to emerald ash borer, white-tailed deer herbivory, and invasive shrubs.

David L. Gorchov is professor of Biology at Miami University. Dave and his graduate and undergraduate students study the patterns and processes of plant invasions in deciduous forests and interactions between invasive plants and deer.

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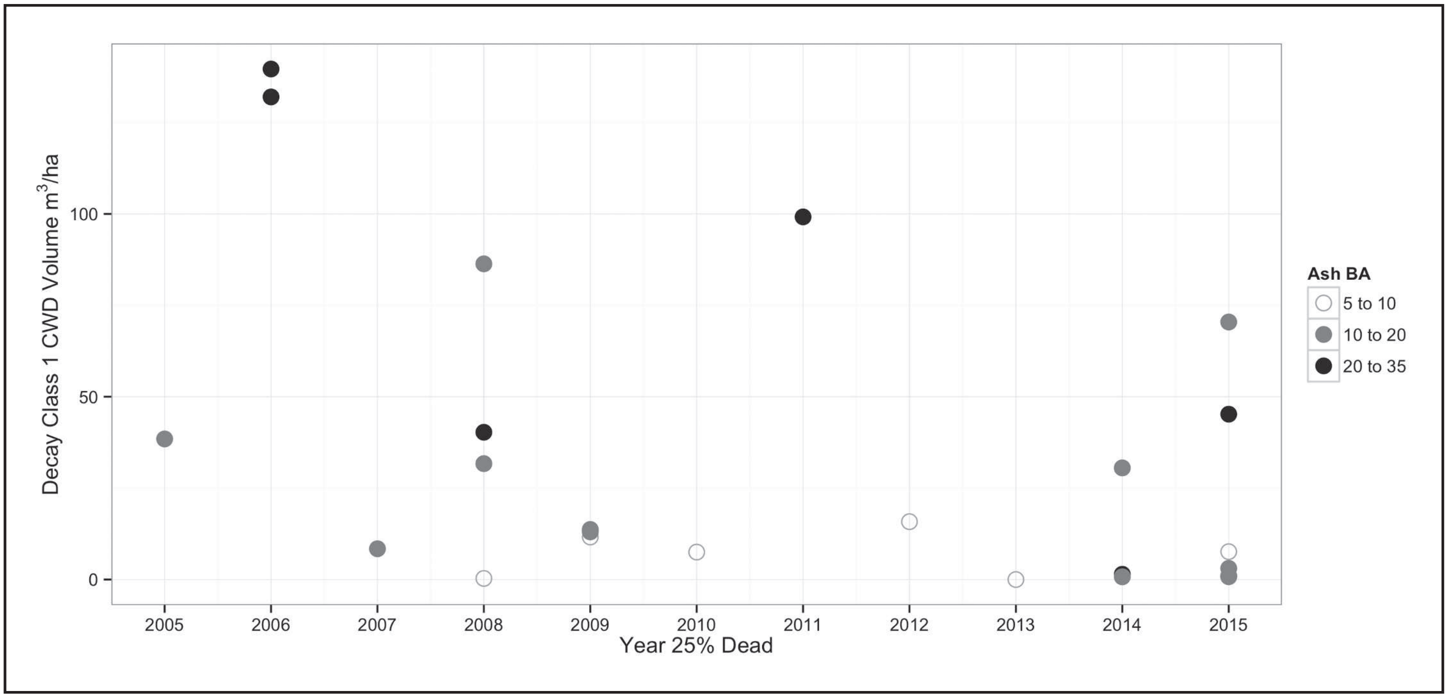

Figure 3. Scatterplot of average decay class 1 coarse woody debris (CWD) volume vs. year when ash mortality reached 25%, stratified by *Fraxinus* basal area (BA) in m^2/ha, among study sites."

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