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Spatial distribution of Callery pear (*Pyrus calleryana*, Rosaceae) in northern Kentucky and southwest Ohio[1]

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Abstract. Callery pear is an invasive nonnative species that was introduced to the United States as an ornamental tree. Previous work on its stand structure has suggested that Callery pear is mid-shade-tolerant or shade-intolerant. The shade tolerance of plants can also be determined by examining their spatial distributions. I selected nine stands dominated by Callery pear in northern Kentucky and southwest Ohio. At each site I laid out a 10 m × 10 m grid and recorded the position of each pear tree, as well as its diameter. Diameters were fit to a two-factor Weibull distribution to determine the shape parameter of diameter distributions. I also determined the pair correlation (nearest neighbor) function $\hat{g}(r)$, which is related to Ripley's K, to look for patterns of distribution. To look for associations among size classes at each stand, bivariate Ripley's $\hat{K}_{12}(r)$ functions were determined. Overall, trees were randomly distributed, with no associations among size classes. However, the smallest size classes often showed clustering, while the larger size classes rarely did. These distribution patterns follow those typically seen in shade-intolerant plants with bird-distributed seeds. While a shade-intolerant species would ordinarily be confined to open and disturbed areas, Callery pear's extended leaf phenology and documented invasion of forests suggest it may become a problem in closed-canopy forests.

Key words: dispersion, invasive species management, Ripley's *K*, shade tolerance, Weibull distribution

Callery pear (*Pyrus calleryana* Decne.) is an invasive nonnative species of tree in the eastern US that is originally from east Asia (Vincent 2005). It has been reported as invasive in 35 states (EDDMapS 2024, USDA PLANTS 2024). 'Bradford', the first horticultural cultivar, was introduced in 1960 as an ornamental tree (Culley 2017, Vincent 2005). Problems with this cultivar led to the development of others, many of which were planted next to existing Bradford trees (Culley 2017, Gilman and Watson 1994). While individual cultivars are self-incompatible, trees of different cultivars can readily breed with each other, and because birds readily eat the fruits, seeds can be spread widely (Culley 2017, Culley et al. 2011, Culley and Hardiman 2009, Hardiman and Culley 2010). This tree forms dense thickets where it invades open and disturbed areas (Vincent 2005, White et al. 2005). Previous research on the stand structure of Callery pear has indicated that the species is shade-intolerant or mid-tolerant (Boyce and Ocasio 2020).

The study of spatial patterns is another way to infer the shade tolerance of tree species. Individuals of most tree species in young stands are found in clustered patterns (Omelko et al. 2018), due to the pattern of seed dispersion. As trees age and self-thinning occurs, these patterns become more random or even uniform; this is especially pronounced in shade-intolerant species (Mast and Veblen 1999, Omelko et al. 2018, Petritan et al. 2014). Ripley's K function (Dale 1999, Diggle 2002) is often used to analyze spatial patterns. When λ is the density of points per unit area, $\lambda K(r)$ equals the number of points within the distance r of a randomly chosen point. If points are distributed randomly, $K(r) = \pi r^2/\lambda$. However, Ripley's K can confound effects at larger distances with those at shorter distances (Getis and Franklin 1987, Penttinen et al. 1992), whereas the pair correlation function $\hat{g}(r)$ (Perry et al. 2006, Wiegand and Moloney 2004) will show only what is occurring at distance r. The pair correlation function is related to Ripley's K function as $g(r) = (dK/dr)(2\pi r)$ and equals the number of points at a distance r from a randomly chosen point. If points are distributed randomly, $\hat{g}(r) = 1$ at all distances r; if points are clustered at a distance r, $\hat{g}(r)$ will be significantly

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Table 1. Site, location, and soil type, along with slope, for each site. Soil types are taken from USDA NRCS (2024); abbreviations in parentheses are map unit symbols used in soil surveys.

Site	Location (latitude, longitude)	Soil Type & Slope, Surrounding Land Use
Alexandria	38°58′18″N, 84°23′28″W	Nicholson silt loam, 2–6 % slopes (NIC) Commercial/residential
Berkshire Rd	39°5′11″N, 84°22′15″W	Bonnell silt loam, 25–35 % slopes (BoE) Residential
Bicentennial Green	39°5′13″N, 84°19′55″W	Urban land-Alfic Udarents-Rossmoyne complex, 0–12 % slopes (UAGXC) Residential
Johns Hill Rd	39°1′37″N, 84°27′42″W	Faywood silty clay loam, 12–20 % slopes (FcD) Residential
Moock Rd	39°3′41″N, 84°28′24″W	Eden silty clay loam, 20–35 % slopes, eroded (EdE2) Residential
Short Park	39°7′49″N, 84°21′46″W	Jules silt loam, occasionally flooded (Ju) Agricultural/park/golf course
Steffen	39°1′34″N, 84°28′8″W	Nicholson silt loam, 6–12 % slopes (NlC) Residential
Tesseneer Rd	39°2′35″N, 84°27′38″W	Faywood silty clay loam, 12–20 % slopes (FcD) Commercial
Union	38°58′5″N, 84°40′21″W	Faywood silty clay, 12–20 % slopes, severely eroded (FdD3) Residential

larger than 1, while it will be significantly below 1 if points are uniformly distributed.

The goal of this project was to determine the spatial patterns in Callery pear stands to infer the shade tolerance of the species. I hypothesized that pear stands, especially with larger, i.e., older, trees, would show random or even uniform distributions, thereby showing that Callery pear is shade-intolerant. However, because seeds are distributed by birds, I also hypothesized that smaller trees would show clustered distributions, while larger trees would exhibit regular or uniform distributions.

Materials and Methods. Nine pear-dominated sites were selected in northern Kentucky and southwest Ohio (Table 1). All sites were near roads and were large enough that a sampling plot could be laid down, and most sites contained few or no other tree species in the overstory. Soil type was determined using the Web Soil Survey (USDA NRCS 2024). At each site, I oriented a 10 m $\times$ 10 m grid to contain what I judged was a representative portion of the stand and recorded the position of each Callery pear tree within the grid. The X and Y coordinates of each tree and the diameter of each shrub at stump height (dsh; 25 cm) were measured. Basal areas were calculated by converting dsh of each tree to dbh (diameter at breast height; 1.37 m) using the allometric relationship derived by Boyce and Ocasio (2020). Diameter distributions at each site were fit to the two-factor Weibull distribution (Coomes and Allen 2007, Lorimer and Krug 1983), as described by Boyce and Ocasio (2020), using the fitdistr function in the MASS library of R (R Core Team 2024). Values of the Weibull shape parameter $a < 1$ show a steeply monotonically declining diameter distribution, while $a = 1$ indicates an exponentially declining distribution. The distribution is a positively skewed unimodal curve when $1 < a < 3.5$, a normal curve when $a = 3.5$, and a negatively skewed unimodal curve when $a > 3.5$. The scale coefficient b is often correlated with mean diameter (Coomes and Allen 2007).

The library splancs in R was used to calculate the pair correlation function $\hat{g}(r)$, using the function Ghat and dividing it by the theoretic values for a random distribution generated by Fzero (R Core Team 2024). To determine the distributions of individual sites and size classes within sites, 10,000 spatially random distributions were generated to derive 95% confidence envelopes for testing for departures from spatial randomness (Diggle 2002, Symanzik 2000). I first determined patterns of dispersion for all trees in each pear stand. I then divided trees into three diameter size classes ($\leq$ 5 cm, $>$ 5–10 cm, and $>$ 10 cm) and determined dispersion patterns in each size class.

To look for associations between size classes at each site, bivariate values of K for pairs of size classes ($K_{12}(r)$) were calculated in splancs with

Table 2. Site, median diameter at stump height (dsh) basal area (BA), and shape parameter from the two-factor Weibull distribution for the stands included in this study. The 95% confidence intervals were bootstrapped with 1,000 permutations.

Site	Median dsh (cm)	Density (ha^{-1})	BA (m^2 ha^{-1})	Shape parameter a ± 95% CI
Alexandria	3.6	5,700	3.55	2.25 (1.88, 2.78)
Berkshire Rd	13.4	2,000	19.18	2.98 (2.12, 4.34)
Bicentennial Green	6.5	3,400	32.14	1.28 (0.99, 1.71)
Johns Hill Rd	7.4	4,600	25.51	2.17 (1.86, 2.58)
Moock Rd	4.8	11,500	20.70	2.16 (1.85, 2.56)
Short Park	10.2	3,800	20.14	3.09 (2.44, 4.06)
Steffen	3.2	12,000	6.70	1.87 (1.61, 2.16)
Tesseneer Rd	16.0	700	14.36	3.08 (1.76, 7.07)
Union	3.1	8,100	6.00	1.61 (1.36, 1.92)

the function k12hat, and a permutation procedure to calculate P-values involved randomly shifting one of the two groups 10,000 times to generate confidence envelopes. A method suggested by Diggle (2002) was used to correct for the edge effects inherent in analyzing plot data in this fashion. This method involves transforming a rectangular area into a torus in which all edges of the plot are contiguous with the opposite edge, thus eliminating edges altogether. To determine if a global pattern of association was present between two groups, for $\hat{K}_{12}(r)$ I calculated the statistic u (Diggle 2002, Lotwick and Silverman 1982):

$$u = \sum_{k=1} \frac{[K_{12}(r_k) - \pi r_k^2]}{r_k^2},$$

where $r_k = (0.1, 0.2, \ldots, 5.0 \text{ m})$ is each interpoint distance class. P-values were derived from the rank of the value of u, calculated from the actual distribution, against the 10,000 values calculated after random displacement of one of the groups.

Results. Callery pear basal areas ranged from about 3.5 to 32 m^2 ha^{-1} (Table 2). The Weibull shape parameters a of all stands were > 1, indicating positively skewed unimodal distributions, although the 95% confidence interval of Bicentennial Green overlapped 1 ($a = 1$ indicates an exponentially declining distribution). This unimodality is also reflected in the dsh histograms, all of which showed unimodal distributions (Fig. 1). Median dsh and the shape parameter a were significantly correlated with each other (Spearman $r = 0.72$, $P = 0.0369$). The actual locations of stems in each stand are shown in Fig. 2, divided into the three diameter classes ($\leq$ 5 cm, > 5–10 cm, and > 10 cm). At sites with median dsh > 10 cm and density $\leq$ 2000 ha^{-1} (Berkshire Rd, Short Park, Tesseneer Rd; Table 1), there was little to no presence of stems < 5 cm dsh (Fig. 2).

When trees of all sizes were considered together, in most stands at most values of r, there were random distributions (Fig. 3). However, four stands showed signs of clustering, generally at distances $r \leq 1$ m: Alexandria (Fig. 3A), Bicentennial Green (Fig. 3C), Steffen (Fig. 3G), and Tesseneer Rd (Fig. 3H; there was also clustering in the 1.6–2.6 m range). Two sites showed evidence of uniformity at some distances: Bicentennial Green (Fig. 3C, > 2 m), and Steffen (Fig. 3G, 0.9 m).

When stems were divided into size classes, however, a consistent pattern developed. The smallest size class ($\leq$ 5 cm) mostly showed clustering (five out of seven sites; Fig. 4). However, only one out of six sites for the intermediate size class (> 5–10 cm) and only one out of six of the largest size class (> 10 cm) showed this condition. Even the one site with clustering in the largest size class showed clustering over a smaller range of values than exhibited by the smaller size classes. Uniform distributions were seen only in the > 10 cm size class at Bicentennial Green (3.4–4.0 m).

Bivariate analyses using $\hat{K}_{12}(r)$ showed no sign of association between any of the size class at sites with multiple size class shown in Fig. 4. All comparisons yielded global values of $P = 0.9999$, indicating no association between the compared size classes (data not shown).

Discussion. When trees of all sizes were considered together, almost half of the sites showed evidence of clustering (Fig. 3). However, size class data suggest that most of this pattern was driven by clustering in the smallest ($\leq$ 5 cm) size class, as clustering in the larger size classes was rarely present (Fig. 4). Of the seven sites that had

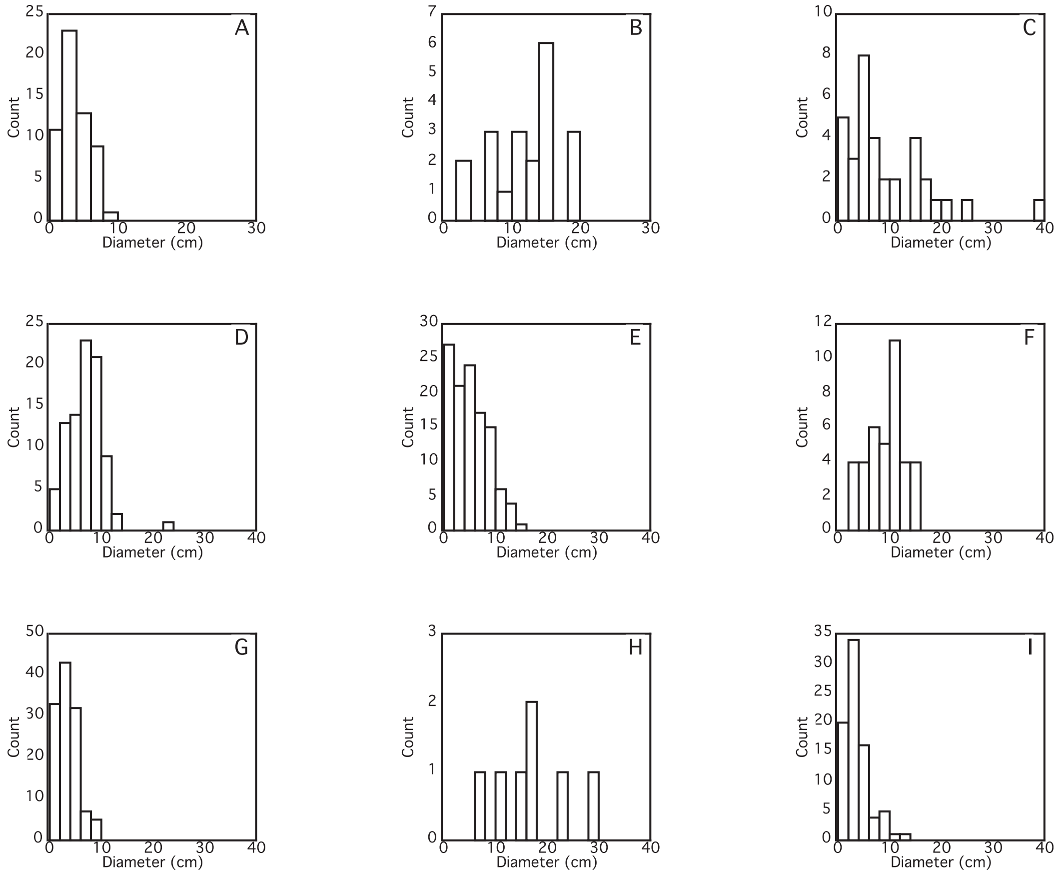

Fig. 1. Histograms showing diameter distributions of pear (dsh; cm) in the sampled stands. A) Alexandria, B) Berkshire Rd, C) Bicentennial Green, D) Johns Hill Road, E) Moock Rd, F) Short Park, G) Steffen, H) Tesseneer Rd, I) Union.

individuals of the smallest size class, five of them showed evidence of clustering at some value of *r* (Fig. 3). Of these five sites, four of them were found on flatter sites with slopes ≤ 12% (Bicentennial Green, Short Park, Steffen) or moderate slopes of 12–20% (Union); only one site was found on a steep slope (Table 1). Bicentennial Green (Fig. 4) was the only site with clustering in the two larger size classes. Comparison of this site with the other sites in Fig. 2 shows that this site has an atypical distribution of trees, with a large cluster in one corner of the plot (Fig. 2C). That corner is near the forest edge, but other plots were also near edges and did not show that type of pattern. Most of the other trees in that plot are in the largest size class, which exhibits a uniform distribution in the 3.4–4.0 m distances. Thus, it is unclear what is responsible for the atypical distribution of pear trees seen at this site.

The development of a random pattern by the time that trees are in the >5–10 cm size class suggests that Callery pear is also shade-intolerant (Fig. 4). The unimodal distribution found in the stands of this study (Table 2, Fig. 1) clearly points toward shade intolerance, as well as the results of the pair correlation functions (Figs. 3–4). The significant relationship between median dsh and the shape parameter *a* is consistent with an increasing tendency toward unimodality with size and age, which is also consistent with shade intolerance. This supports the previous size structure work by Boyce and Ocasio (2020), which indicated that pear is either shade-intolerant or mid-tolerant. Individuals of most tree species start in a clustered pattern, especially at small distances (Omelko et al. 2018), due to the pattern of seed dispersion or heterogeneity in favorable microsites (e.g., Pauchard et al. 2016). Patterns become more random or

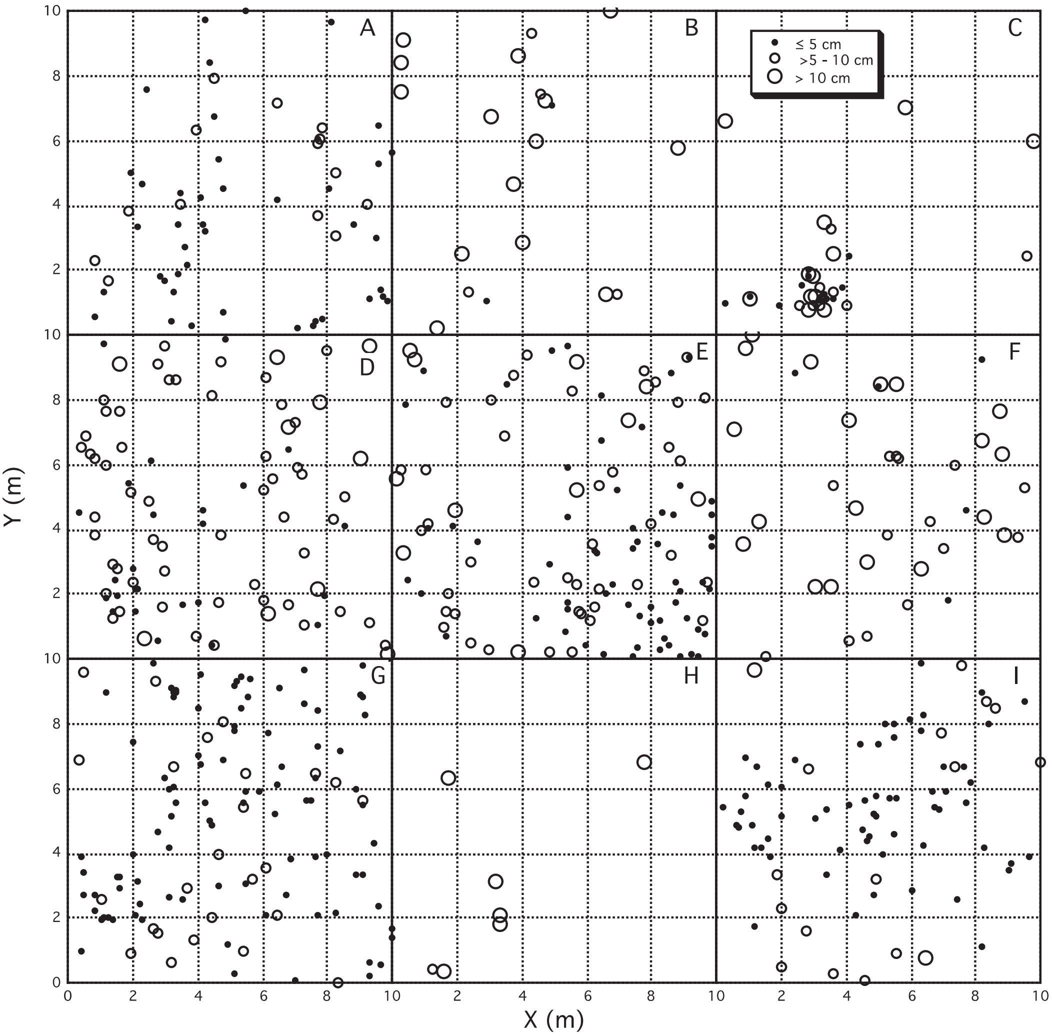

FIG. 2. Mapped distributions of pear trees in each stand. Symbols refer to different dsh size classes. Orientation is not aligned with a particular direction, as it was determined by stand shape and orientation. A) Alexandria, B) Berkshire Rd, C) Bicentennial Green, D) Johns Hill Road, E) Moock Rd, F) Short Park, G) Steffen, H) Tesseneer Rd, I) Union.

even uniform, especially for shade-tolerant species, as trees age and self-thinning commences (Mast and Veblen 1999, Omelko et al. 2018, Petritan et al. 2014). This rapid progression from a clustered to a random pattern is evident even in the sapling stage of shade-intolerant species (Brown et al. 2020, Castellano and Boyce 2007). For example, Brown et al. (2020) found that the most shade-intolerant species in their study were either randomly or uniformly distributed, while the most shade-tolerant species were clustered around others of the same species. Castellano and Boyce (2007) found that shade-tolerant *Lonicera maackii* (Rupr.) Herder (Amur honeysuckle) showed clustering at short distances and between individuals of different sizes, while shade-intolerant *Juniperus virginiana* L. (eastern red cedar) showed mainly random distributions, with no clustering between individuals of different sizes. Thus, the spatial pattern seen for Callery pear in this study is most consistent with a shade-intolerant species.

Three sites, Berkshire Rd, Bicentennial Green, and Tesseneer Rd, were all characterized by larger trees that had mainly random or uniform distributions (Fig. 4). Bicentennial Green and Tesseneer Rd were both characterized by an understory of Amur honeysuckle with an overstory of Callery pear (R. Boyce, personal

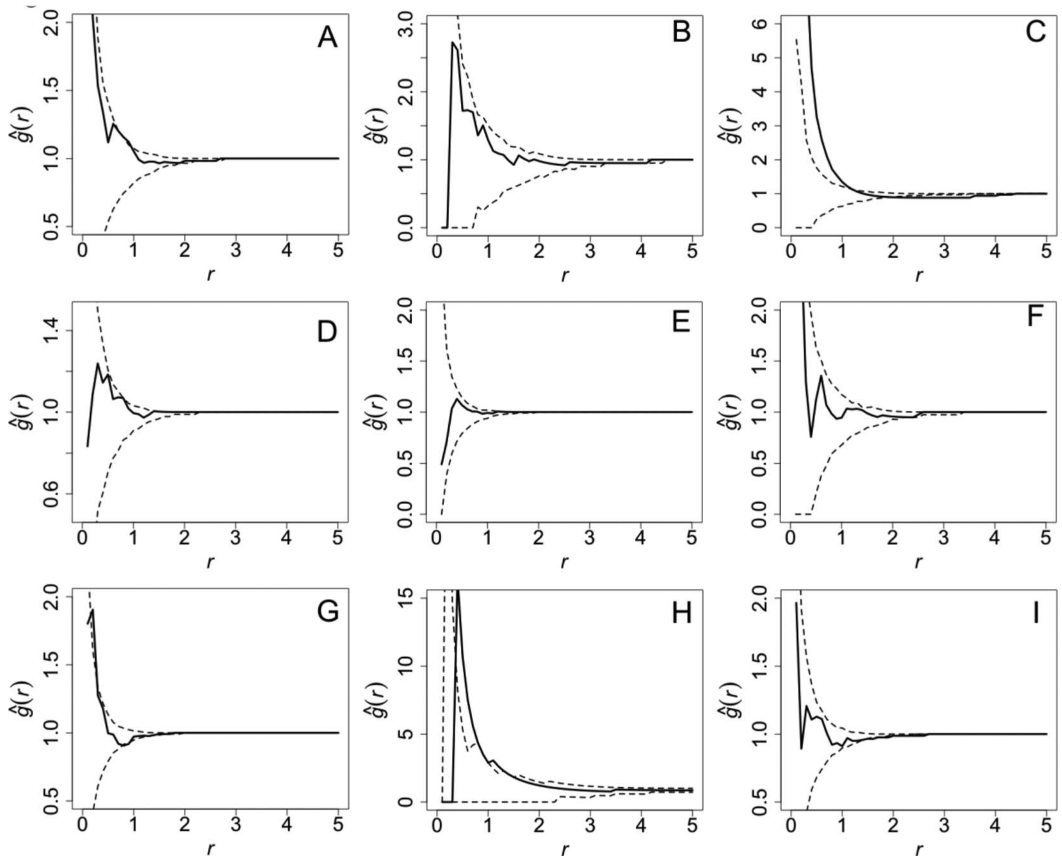

FIG. 3. Pair correlation $g(r)$ functions of all pear trees in each stand. Dashed lines indicate 95% confidence envelopes after 10,000 data randomizations. A solid line above the envelope shows clumping, a solid line within the envelope indicates a random distribution, and a solid line below the envelope indicates a uniform distribution at each distance r. A) Alexandria, B) Berkshire Rd, C) Bicentennial Green, D) Johns Hill Road, E) Moock Rd, F) Short Park, G) Steffen, H) Tesseneer Rd, I) Union.

observations). These sites appear to have originally been open areas that would have been good candidates for colonization by both species. It is likely that the different growth forms of the two species allow them to coexist after colonization by both occurs.

This study was carried out on 10 m × 10 m plots, which are relatively small. Other distribution patterns could appear at larger scales. However, it is difficult to find larger pear-dominated stands. In addition, the focus of this study was at a relatively small scale, as that is where differences in shade tolerance are likely to express themselves, especially when trees are still small. Nonetheless, the findings of this study raise a number of questions. I found pear stands on a variety of slopes (Table 1), but the sample size is too small to determine if there is a preference for a particular topographic position. All of the soils in this study are silty, so there is currently no information on pear stands growing in sandy or clay-dominated soils. Also, all of the stands in this study were pear-dominated, but Callery pear may behave differently in the presence of other early-successional shade-intolerant trees such as *J. virginiana*. The invasive shrubs Amur honeysuckle and multiflora rose (*Rosa multiflora* Thunb.) also occurred in many of the stands in this study, and interactions with these species may affect spatial patterning of Callery pear. There is some indication in this study that pear may not be able to reproduce under its own shade, as stands with large median dsh had little to no small pear individuals, but further work is needed. All stands were found in areas where the surrounding land use often has Callery pear plantings that can serve

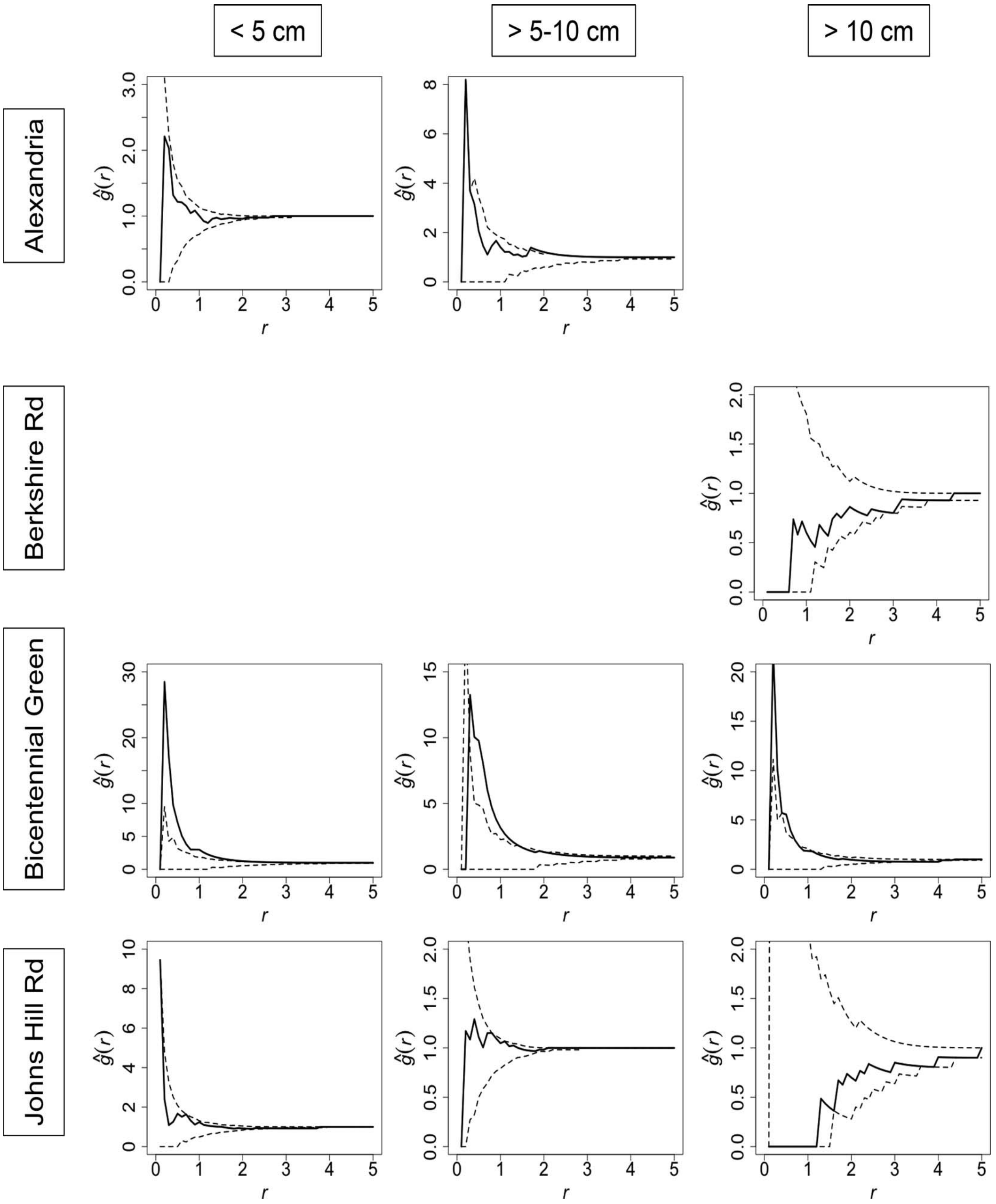

FIG. 4. Pair correlation $g(r)$ functions of pear trees in each stand, by size class. Dashed lines indicate 95% confidence envelopes after 10,000 data randomizations. A solid line above the envelope shows clumping, a solid line within the envelope indicates a random distribution, and a solid line below the envelope indicates a uniform distribution at each distance *r*.

as seed sources, but the unknown land use history of most of the sites in this study may have also contributed to the observed spatial patterns. Most of the stands in this study contained or were near an edge, and spatial patterning in edges may differ from interiors. Finally, the pattern of dispersion by native trees is unknown, as well as how that may affect spatial patterning of Callery pear.

My results suggest that Callery pear may not become an important invader of closed-canopy

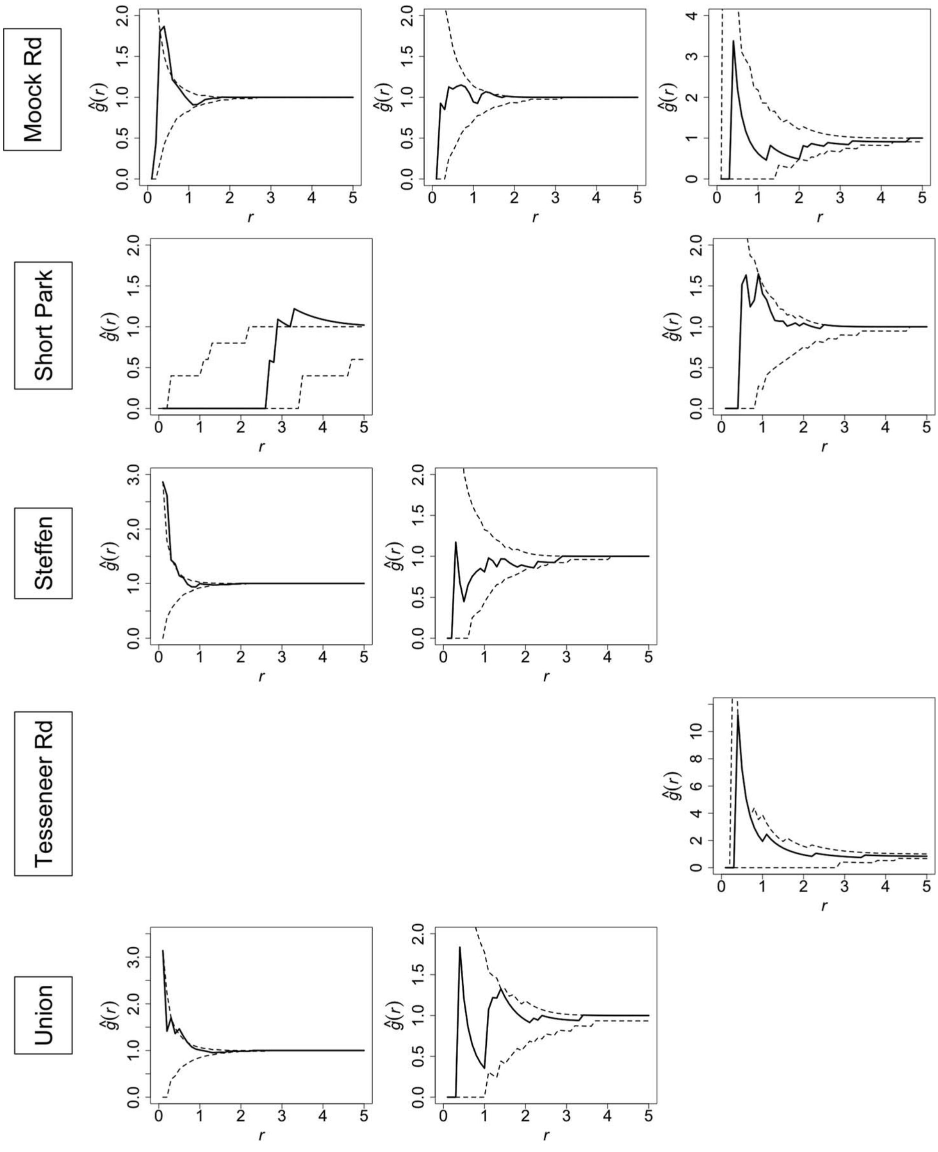

FIG. 4. Continued.

forest stands like the shade-tolerant Amur honeysuckle, as pear is shade-intolerant, but it will still be an important invader in open and disturbed areas. However, Callery pear's biology appears to be like that of autumn olive (*Elaeagnus umbellata* Thunb.). Autumn olive has been described as shade-intolerant to mid-tolerant (Sather and Eckardt 1987). However, it has been found to invade forest interiors from edges (Yates et al. 2004). This may be because autumn olive has extended leaf phenology, which allows it to invade forest understories (Riffe 2018). Maloney et al. (2022) found that Callery pear also has extended leaf phenology; while those researchers focused on the competitive advantage gained by it in open areas, those advantages would also apply to the forest understory. Ash (*Fraxinus* spp.) decline caused by the emerald ash borer (*Agrilus planipennis*) has also opened gaps in forests that might be colonized by Callery pear; for example, Amur honeysuckle increased its growth in forests affect by ash decline (Hoven et al. 2017). Future work is needed to determine the success and persistence of pear within intact forests.

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