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Evaluation of phenological indicators for optimizing spring southern pine beetle (Coleoptera: Curculionidae: Scolytinae) trapping surveys

*John W. Thomason[1], Stephen Clarke[2], and John J. Riggins[1,]**

Abstract

Since 1987, as many as 16 southeastern US states participate in a 4 wk annual spring *Dendroctonus frontalis* (Zimmerman) (Coleoptera: Curculionidae) trapping survey. The purpose of the survey is to assess the current *D. frontalis* outbreak potential, and anticipate prevention and suppression needs for the coming yr. This prediction system relies on capturing the peak *D. frontalis* spring dispersal, thus timing of trap deployment is crucial. Forest managers traditionally attempt to deploy traps at the onset of flowering dogwood (*Cornus florida* L.; Cornaceae) bloom, which is commonly assumed to coincide with peak *D. frontalis* spring dispersal. The objective of this study is to examine the validity of dogwood bloom as an indicator of peak *D. frontalis* spring dispersal. Yr-round trapping data in 2014 and 2015 from Mississippi and Florida were used to identify peak *D. frontalis* and *Thanasimus dubius* (Fabricius) (Coleoptera: Cleridae) dispersal periods. Peak *D. frontalis* dispersal then was compared with dogwood blooming dates from the USA National Phenology Network and personal records. Then, both dogwood bloom dates and peak *D. frontalis* dispersal were compared with timing of actual historic state *D. frontalis* trapping efforts. We also compared peak *D. frontalis* dispersal with *T. dubius* peak dispersal, because *T. dubius* trap captures are used in the prediction model. Last, we examined the utility of extending the spring survey to 6 wk by comparing the 4 wk peak *D. frontalis* trap captures with a corresponding 6 wk peak. On average, mean onset of dogwood bloom occurred 3 wk after the peak 4 wk period of *D. frontalis* flight activity. The average *T. dubius* peak dispersal occurred 1.5 wk after peak *D. frontalis* dispersal. The 6 wk extension provided only a 12% overall average increase in *D. frontalis* trap captures. Eastern redbud (*Cercis canadensis* L.; Fabaceae) also had been suggested as a replacement trap deployment cue; therefore, eastern redbud and flowering dogwood blooming dates in 2019 were monitored on a Mississippi State University property in Oktibbeha County, Mississippi, USA. On this site eastern redbud trees bloomed on average 2.3 wk before the average bloom date of flowering dogwood trees.

Key Words: bloom; *Cercis canadensis*; *Cornus florida*; *Dendroctonus frontalis*; monitoring

Resumen

Desde el 1987, hasta 16 de los estados del sureste de los Estados Unidos han participado en un sondeo anual de captura de *Dendroctonus frontalis* (Zimmerman) (Coleoptera: Curculionidae) por 4 semanas en la primavera. El propósito del sondeo es evaluar el potencial actual de brote de *D. frontalis* y anticipar las necesidades de prevención y supresión para el próximo año. Este sistema de predicción se basa en capturar el pico de dispersión de *D. frontalis* en la primavera, por lo que el momento del despliegue de la trampa es crucial. Los administradores forestales tradicionalmente intentan desplegar trampas al inicio de la floración del cornejo (*Cornus florida* L.; Cornaceae), que comúnmente se supone que coincide con el pico de dispersión de *D. frontalis* en la primavera. El objetivo de este estudio es examinar la validez de la floración del cornejo como indicador del pico de dispersión de *D. frontalis* en la primavera. Se utilizaron datos de captura de todo el año en el 2014 y 2015 de Mississippi y Florida para identificar los períodos de pico de dispersión de *D. frontalis* y *Thanasimus dubius* (Fabricius) (Coleoptera: Cleridae). Luego, se comparó el pico de dispersión de *D. frontalis* con las fechas de floración del cornejo de la Red Nacional de Fenología de EE.UU. y los registros personales. Luego, se compararon las fechas de floración del cornejo y la dispersión máxima de *D. frontalis* con el cronometraje del estado histórico real de los esfuerzos de captura de *D. frontalis*. También, comparamos el pico de dispersión de *D. frontalis* con el pico de dispersión de *T. dubius*, porque las capturas de trampa de *T. dubius* se utilizan en el modelo de predicción. Por último, examinamos la utilidad de extender el sondeo de la primavera a 6 semanas comparando los picos de las capturas de trampa de *D. frontalis* de 4 semanas con los picos correspondientes de 6 semanas. Por general, el inicio de la floración del cornejo empieza 3 semanas después del pico de período de 4 semanas de actividad de vuelo de *D. frontalis*. El promedio del pico de dispersión de *T. dubius* ocurrió 1.5 semanas después del pico de dispersión de *D. frontalis*. La extensión de 6 semanas proporcionó solo un aumento promedio general del 12% en las capturas de trampas de *D. frontalis*. También, se había sugerido el ciclamor de Canadá (*Cercis canadensis* L.; Fabaceae) como señal para desplegar el reemplazo de la trampa; por lo tanto, las fechas de floración de ciclamor de Canadá y cornejo en floración en el 2019 se monitorearon en una propiedad de la Universidad Estatal de Mississippi en el condado de Oktibbeha, Mississippi, EE. UU. En este sitio, los árboles de ciclamor de Canadá florecieron en un promedio de 2.3 semanas antes de la fecha promedio de floración de los árboles de cornejo.

Palabras Clave: floración; *Cercis canadensis*; *Cornus florida*; *Dendroctonus frontalis*; monitoreo

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The ability to understand and predict key life history events for insect pests plays a vital role in their management (Ham & Hertel 1984; Clarke et al. 2016). For instance, the pales weevil, *Hylobius pales* (Herbst) (Coleoptera: Curculionidae) is attracted to fresh cut pine stands. If a stand is replanted too early, their brood can decimate the newly planted pine seedlings. Forest managers may employ a silvicultural control tactic of cutting early in the yr (before Jul) and planting the following winter, allowing the pales weevil to complete its life cycle and leave the stand before the seedlings are planted (Nord et al. 1984). The Nantucket pine tip moth, *Rhyacionia frustrana* (Comstock) (Lepidoptera: Tortricidae) can be a pest of young pine and Christmas tree plantations. Insecticide sprays may be used to control their populations (Berisford et al. 1984). However, effective control requires nursery managers to be able to predict *R. frustrana* egg hatch and larval development in order to time the application of insecticides to coincide with these life history events (Douce et al. 2002). The aforementioned examples express why researchers have developed predictive models (Gargiullo et al. 1985; Kumral et al. 2007; Knutson & Muegge 2010; Akotsen-Mensah et al. 2011; Haavik et al. 2013) or observational cues (Mussey & Potter 1997; Herms 2004; Reding et al. 2013; Hartshorn et al. 2016) to predict key life history events for many serious insect pests.

The southern pine beetle, *Dendroctonus frontalis* (Zimmerman) (Coleoptera: Curculionidae), can be a severe pest of all southern pine species, but most notably loblolly pine (*Pinus taeda* L.), shortleaf pine (*Pinus echinata* Mill.), slash pine (*Pinus elliottii* Englm.), and longleaf pine (*Pinus palustris* Mill.) (all Pinaceae) (Payne 1980; Blanche et al. 1983). Approximately 84% of total pine timber losses across 10 southeastern states of the US between 1977 and 2004 can be attributed to 4 large *D. frontalis* outbreaks (Pye et al. 2004).

A regional annual *D. frontalis* risk assessment survey was developed in the 1980s and became an important part of the integrated pest management strategy developed for *D. frontalis* (Billings 1988; Billings & Upton 2010). The survey is an early warning system used to predict the *D. frontalis* population status and infestation trends for the current yr. This prediction allows forest managers to appropriate adequate resources to address potential *D. frontalis* outbreaks (Billings & Upton 2010). The survey is conducted currently over a consecutive 4 wk period in the spring using Lindgren 12-unit funnel traps (Lindgren 1983) baited with polyethylene bags containing 70% α and 30% β pinene (released at about 5 g per d) along with *D. frontalis* aggregation pheromones frontalin (released at about 5 mg per d) and endo-brevicomin (Billings 2011; Sullivan 2016). State and federal forest agencies deploy traps in the host pine forests throughout each of the 16 participating states (Billings 2011). Trap catches are collected weekly, and numbers of *D. frontalis* and their most significant invertebrate predator, the checkered clerid beetle, *Thanasimus dubius* (Fabricius) (Coleoptera: Cleridae), are tallied. The mean number of *D. frontalis* per trap per d and the ratio of *D. frontalis* to *T. dubius* are used to derive a prediction for a given locality. The predictions were initially obtained from a chart developed and revised by the Texas Forest Service (Billings & Upton 2010).

The survey's ability to accurately assess *D. frontalis* population levels has been variable in recent yr. In Mississippi, outbreaks occurred on the Homochitto National Forest in 2012, the Tombigbee National Forest in 2014, and the Bienville National Forest in 2015 (Asaro et al. 2017); however, the survey projected population trend/levels to be static/low, decreasing/moderate, or increasing/low, respectively, for each outbreak occurrence (Table 1). A variety of factors may affect the predictive power of the survey. The chemistry of lures used was changed in 2007, because polyethylene bags of (70% α-pinene to 30% β-pinene) replaced steam-distilled turpentine volatilized from a wicked bottle as the host compound component (Billings 2011). This change was due to a lack of commercially available sources of turpentine (Sullivan 2016). Endo-brevicomin, which synergizes the attractiveness of the frontalin lure (Sullivan & Mori 2009), is now also included (Billings 2017). In addition, trap placement recommendations have changed, because traps must be placed 20+ m from the nearest host pine to reduce the risk of spillover attacks on adjacent pines now that endo-brevicomin is used (Stephen Clarke, personal communication).

In addition to the factors detailed above, the trap timing is important in ensuring an accurate assessment of existing spring *D. frontalis* population levels. Trap deployment must coincide with the peak of *D. frontalis* spring flight activity (Billings & Upton 2010). Spring *D. frontalis* flight activity generally occurs within a 3 mo time frame, usually with a 3 to 6 wk peak period (Friedenberg et al. 2007). Predicting the peak is difficult because all life stages of *D. frontalis* overwinter (Lombardero et al. 2000). Further development or even emergence can occur during periods of favorable winter temperatures (Moser & Dell 1979). Climate change may also affect the timing of bark beetle spring dispersal flight (Jönsson et al. 2009; Milton & Ferrenberg 2012). Multiple emergence peaks due to variable spring temperatures may influence population levels in subsequent mo because they may affect the ability of *D. frontalis* to allocate a sufficient number of beetles to mass attack pines and initiate an infestation (Friedenberg et al. 2007). Therefore, it is crucial that forest managers have a practical means of predicting the peak or peaks of spring dispersal by *D. frontalis*.

Peak spring dispersal of *D. frontalis* has been anecdotally associated with the blooming phenology of various indigenous tree species (Hopkins 1909). Flowering of eastern redbud (*Cercis canadensis* L.; Fabaceae) (St. George & Beal 1929), pollen release of loblolly pine (*P. taeda*) (Billings 1988), and flowering of flowering dogwood (*Cornus florida* L.; Cornaceae) (Thatcher & Barry 1982; Billings 1988) all have been suggested as indicators for the onset of peak *D. frontalis* spring dispersal. The onset of flowering dogwood bloom was the protocol for trap deployment of the annual spring *D. frontalis* risk assessment survey for several decades (Billings 1988). Because the actual flowers of flowering dogwood are inconspicuous, the onset of bloom refers to the white bracts that open before the flower buds. In 2017, regional spring trapping guidelines from the USDA Forest Service were revised to suggest the use of the bloom of redbuds instead of dogwoods as a phenological cue for peak *D. frontalis* spring dispersal (Billings 2017).

The synchronicity between peak spring *D. frontalis* dispersal and the phenology of local tree species have been based solely on observations, and analyses to assess these claims are lacking. Sub-optimal timing of trapping may have contributed to the recent failures of the annual survey to accurately predict local outbreaks. Therefore, we conducted studies to (1) quantify if recent survey dates were optimally timed to encompass the peak in *D. frontalis* spring dispersal, (2) deter-

Table 1. *Dendroctonus frontalis* outbreaks in Mississippi and the prediction results from the annual spring survey.

Outbreak	% *Dendroctonus frontalis*	*Dendroctonus frontalis* per trap per d	Clerids per trap per d	Prediction	New spots[a]
Homochitto 2012	6	0.8	11.5	Static/low	793
Tombigbee 2014	18	15.5	69.2	Decreasing/ moderate	180
Bienville 2015	33	2.5	5	Increasing/low	238

[a] Spot data collected from the Southern Pine Beetle Information System.

mine if the onset of flowering dogwood bloom is a good predictor of peak *D. frontalis* flight activity, (3) compare bloom phenology of redbud and dogwood trees, and (4) evaluate the viability of a 4 to 6 wk survey for describing *D. frontalis* spring flight activity.

Materials and Methods

DENDROCTONUS FRONTALIS TRAPPING

We conducted yr-round *D. frontalis* trapping to monitor flight activity to identify when peak spring dispersal occurred for a given location. Two Mississippi locations (Oktibbeha County and Homochitto National Forest) and 1 in Alachua County, Florida, USA, were surveyed; henceforth these trapping locations will be referred to as Oktibbeha, Homochitto, and Alachua. There were 2 trap sites in 2014 and 5 trap sites in 2015 in Oktibbeha (Table 2). The number of trapping sites remained constant throughout the study period for both Alachua and Homochitto, with 1 and 3 sites, respectively. The traps remained deployed for the entirety of 2014 and 2015 except in 2014 on the Homochitto, when the traps were taken down on 6 May 2014 and redeployed 1 Jan 2015. The extended trap deployment required lures to be changed every 4 wk to ensure the baits remained attractive to *D. frontalis*. All Lindgren 12-funnel traps were baited identically to the annual spring survey traps. All lures were purchased from Synergy Semiochemicals Corporation (Vancouver, British Columbia, Canada). The frontalin and pinene lures were affixed to the trap while the endo-brevicomin was attached to a twig approximately 4 m from the trap (Sullivan & Mori 2009). All trap locations were 20+ m from the nearest pine in hardwood bottom lands adjacent to pine stands. Traps were hung so that the collection cups were approximately 1 to 2 m above the ground, maintaining uniformity with the spring survey trapping. All trap captures were collected weekly.

For the purposes of this study, we considered the potential spring flight season of *D. frontalis* to occur between 1 Jan and 31 May of each yr. This 5 mo range was early enough to capture the earliest late winter flights (Moser & Dell 1979), and long enough to allow the spring dispersal flight to conclude. The weekly *D. frontalis* and *T. dubius* captures from yr-round traps were tallied and recorded by location and trap. Then all traps in a location were summed to provide the weekly total of *D. frontalis* and *T. dubius* trap captures for each location. The peak *D. frontalis* and *T. dubius* spring dispersal period was defined as the continuous 4 wk period that the observed trap captures were greater than any other continuous 4 wk period. Weekly totals also were converted to a percentage of the 5 mo total spring trap captures to evaluate the yearly variation in population size (Akotsen-Mensah et al. 2011). The percentage of all beetles collected during the peak period was calculated.

Table 2. Trap site coordinates for monitoring 2014 and 2015 yr-round *Dendroctonus frontalis* flight activity.

Trap	Oktibbeha, Mississippi	Homochitto, Mississippi	Alachua, Florida
1	33.367°N, 88.861°W	31.392°N, 91.054°W	29.743°N, 82.468°W
2	33.342°N, 88.880°W	31.406°N, 91.130°W	
3	33.306°N, 88.906°W[a]	31.458°N, 91.193°W	
4	33.469°N, 88.905°W[a]		
5	33.606°N, 88.947°W[a]		

[a]These traps were added in 2015.

PEAK DISPERSAL WEEKS VS. SURVEY TRAPPING DATES

The annual 4 wk spring survey trapping dates conducted in Mississippi and Florida by state and federal government agencies were compared to the peak trap captures to determine if the surveys coincided with the peak *D. frontalis* spring dispersal. Only surveys conducted in the same or adjacent counties to the yr-round trapping sites were used in the analyses.

DENDROCTONUS FRONTALIS DISPERSAL VS. FLOWERING DOGWOOD BLOOM

Peak *D. frontalis* spring dispersal periods were compared also to flowering dogwood blooming dates. Because *D. frontalis* spring dispersal periods vary greatly at different latitudes (Billings & Upton 2010), trapping sites were compared only to flowering dogwood bloom phenology sites within the same plant hardiness zone. We used the 2012 USDA plant hardiness zone map (https://planthardiness.ars.usda.gov/), which at that time was the most current. Both Homochitto and Alachua trap sites were in zone 8B, whereas Oktibbeha trap sites were in zone 8A.

We obtained flowering dogwood blooming dates from 3 sources. One source was the USA National Phenology Network (www.usanpn.org), which provided bloom phenology across the southeastern US for both yr of the study. Another source was the Dogwood Bloom Watch Blog (http://dogwoodbloomwatch.blogspot.com), which provided time stamped photographs depicting dogwood bloom phenology along with a written assessment on the progression of dogwood bloom in the Davey Dogwood Park in Palestine, Texas, USA. We also monitored and recorded dogwood blooming dates for 2015 in Oktibbeha County, Mississippi. These records consisted of tagging and monitoring a patch of flowering dogwoods (33.475129°N, 88.793119°W) in an unmanaged woodlot on the periphery of the Thad Cochran Research, Technology & Economic Development Park at Mississippi State University, in Starkville, Mississippi, USA. Trees were monitored from 8 Mar to 4 Apr and checked at least twice per wk until mostly in full bloom. All 3 sources were used to determine the median date of the onset of dogwood bloom, which for the purposes of this research was the earliest date for a tree to have at least 1 bud displaying white bracts. For plant hardiness zone 8A there were 6 records for dogwood bloom in 2014 and 3 records in 2015. For plant hardiness zone 8B there were 3 records for dogwood bloom in 2014 and 2 records in 2015.

FLOWERING DOGWOOD BLOOM VS. EASTERN REDBUD BLOOM

Bloom dates of flowering dogwood and eastern redbud were monitored during spring 2019 at the same unmanaged woodlot (Oktibbeha County, Mississippi) that flowering dogwood bloom was monitored in 2015. Twenty-five trees of each species were tagged on 1 Feb and monitored for bloom every 2 to 3 d until 29 Mar when the last tagged tree had 1 or more blooms. Because the recommended use of redbud bloom as an indicator for *D. frontalis* survey timing was a recent development, we did not have the resources to monitor yr-round *D. frontalis* traps at the time. Though we could not directly compare redbud bloom, dogwood bloom, and peak *D. frontalis* dispersal, we were able to examine the phenological relationship between eastern redbud bloom and flowering dogwood bloom.

UTILITY OF A 4 TO 6 WEEK TIMEFRAME TO DESCRIBE *DENDROCTONUS FRONTALIS* FLIGHT ACTIVITY IN THE SPRING

The percentage of *D. frontalis* captured during the 4 wk period of peak dispersal was calculated for each site and yr, as well as the number of apparent flight peaks. Given that the efficacy of the lures can persist for up to 6 wk, we also examined if lengthening the time frame enabled the survey to cover multiple peaks, if present. The maximum percentage of *D. frontalis* collected in any 6 wk period was calculated.

Results

PEAK *DENDROCTONUS FRONTALIS* DISPERSAL WEEKS VS. SURVEY TRAPPING DATES

Compared to the consecutive 4 wk peak spring dispersal period, annual state and federal spring surveys began an average of 3 wk after the start of peak *D. frontalis* spring dispersal (Table 3; Fig. 1). The survey and 4 wk peak flight activity coincided only once, in 2014 on the Homochitto National Forest (Fig. 1). In 2 instances, peak flight had concluded prior to the survey (Oktibbeha and Alachua 2015), and once the survey initiated and concluded before peak dispersal began (Alachua 2014). Peak flight activity began earlier in 2015 than in 2014: 1 wk on the Homochitto, 8 wk in Oktibbeha, and 6 wk in Alachua.

DENDROCTONUS FRONTALIS DISPERSAL VS. FLOWERING DOGWOOD BLOOM

Overall, only 25.7 ± 6.51 standard error (SE) of the total spring *D. frontalis* trap captures coincided with a consecutive 4 wk period beginning with the median onset of dogwood bloom (Table 3). Peak *D. frontalis* spring dispersal often was earlier than dogwood bloom, offset by 1 to 9 wk at various locations during this study. The 2014 and 2015 mean percentages of *D. frontalis* trap captures preceding dogwood bloom across all locations were 53.9 and 77.1%, respectively (Table 3). The use of dogwood bloom as an indicator to initiate trapping was inconsistent, as 3 of 6 of the spring surveys began at least 2 wk prior to its onset (Fig. 1).

FLOWERING DOGWOOD BLOOM VS. EASTERN REDBUD BLOOM

Eastern redbud bloom occurred approximately 2.3 wk before flowering dogwood bloom in 2019 (Fig. 2). The mean (± SE) onset of eastern redbud bloom occurred 10.6 ± 0.13 wk after the first of the yr, vs. the mean onset of flowering dogwood bloom which occurred 12.9 ± 0.07 wk after the first of the yr. The variability of onset of bloom dates was over 2**×** greater in redbuds than in dogwoods, with 2.4 wk between the first and last eastern redbud bloom dates, and only 1.1 wk between first and last bloom dates for flowering dogwood trees (Fig. 2).

UTILITY OF A 4 TO 6 WK TIMEFRAME TO DESCRIBE *DENDROCTONUS FRONTALIS* FLIGHT ACTIVITY IN THE SPRING

Across all locations and years, a 4 wk peak dispersal period accounted for 45% ± 3.2 SE of the total spring *D. frontalis* trap captures (Table 3). During the 4 wk in 2014 and 2015 that the *D. frontalis* spring surveys were conducted, the mean captures in our yr-round traps were only 26.8% ± 4.98 SE of the total spring *D. frontalis* trap captures (Table 3).

Peak spring dispersal at Oktibbeha accounted for 57% of the total spring dispersal in 2014 and 42% in 2015. On the Homochitto, 43% and 35% of *D. frontalis* collected were captured during the peak periods in 2014 and 2015, respectively. *Dendroctonus frontalis* collections in Alachua followed a similar pattern, with a greater percentage (51%) captured during the peak period in 2014 than in 2015 (42%).

Collection numbers were multimodal in all locations in both yr (Fig. 3). Expanding the determination of peak dispersal to 6 wk, the maximum field life of the lures, increased the percent of *D. frontalis* collected to 57% ± 3.2 SE overall, only a 12% increase (range 10–17%). In only 2 instances (Homochitto 2014 and Alachua 2015) did the use of a 6 wk period allow a marginal detection of multiple peaks, and the overall average peak to peak separation was 6.5 wk (Fig. 3).

DENDROCTONUS FRONTALIS PEAK DISPERSAL VS. *THANASIMUS DUBIUS* PEAK DISPERSAL

For all yr and locations, the average 4 wk peak dispersal of *T. dubius* occurred 1.5 wk after peak *D. frontalis* dispersal. The overall mean peak of *T. dubius* and *D. frontalis* 4 wk dispersal occurred 11 **±** 0.8 SE and 9.5 ± 1.5 SE weeks after the first of the yr, respectively. Overlap between peaks of *D. frontalis* and *T. dubius* collections always were present except in Oktibbeha 2015. There were no substantial *T. dubius* trap captures before Feb; however, in 4 instances (Homochitto 2014; Oktibbeha 2015; Homochitto 2015; and Alachua 2015) substantial *D. frontalis* trap captures occurred in Jan (Fig. 3).

Discussion

The ability of the *D. frontalis* spring survey to predict outbreaks has been unreliable in recent yr (Table 1), potentially due in part to sub-optimal timing of trap deployment. Despite historical anecdotes to the contrary, dogwood bloom proved to not be an effective predictor of *D. frontalis* spring dispersal. Within the confines of this study, the best case scenario for using dogwood bloom as the phenological

Table 3. The timing of flowering dogwood bloom (DW) peak, *Dendroctonus frontalis* – southern pine beetle (SPB) spring dispersal, and initiation of annual *Dendroctonus frontalis* spring survey along with the corresponding percentage of *Dendroctonus frontalis* captured in nearby yr-round traps.

Median DW bloom date	Latest date to capture peak SPB dispersal	Initiation of survey trapping	%SPB trap captures before DW bloom date[a]	%SPB trap captures if DW initiated trapping[a]	%SPB trap captures during actual 4 wk survey tapping	%SPB trap captures during optimal 4 wk peak
12 Apr 2014	20 Mar 2014	9 Apr 2014	69	27	28	57
22 Mar 2014	11 Mar 2014	11 Mar 2014	48	41	43	43
22 Mar 2014	10 Mar 2014	17 Feb 2014	45	42	29	51
		$\bar{x}$	53.9	36.8	33.3	50.3
31 Mar 2015	21 Jan 2015	7 Apr 2015	85	12	6	42
19 Mar 2015	4 Mar 2015	23 Mar 2015	54	30	32	35
19 Mar 2015	27 Jan 2015	27 Feb 2015	92	2	23	42
		$\bar{x}$	77.1	14.7	20.3	39.7
		Overall $\bar{x}$	65.5	25.7	26.8	45.0

[a] Based on median of flowering dogwood bloom date.

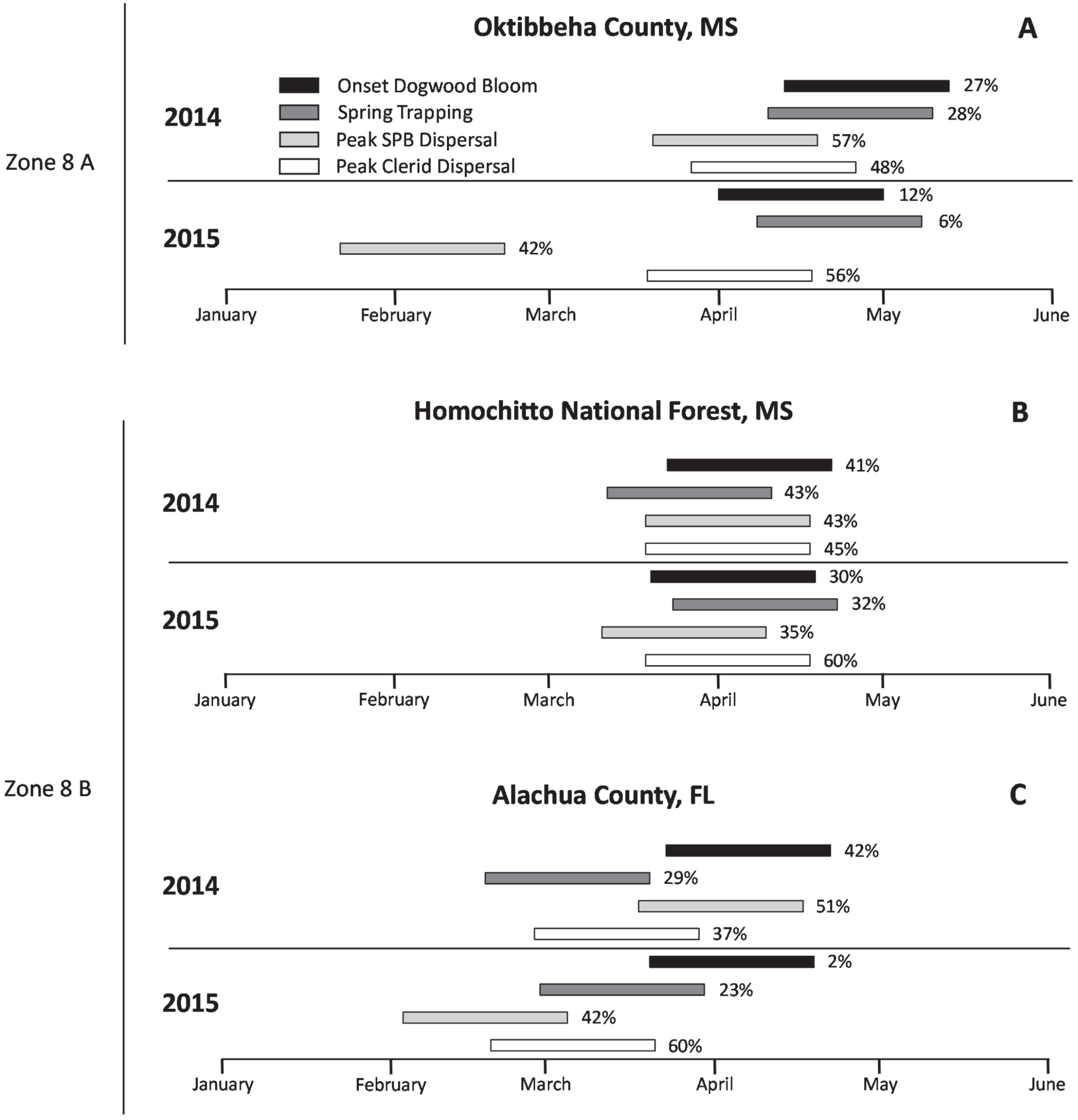

Fig. 1. Comparison of dogwood bloom dates, *Dendroctonus frontalis* (southern pine beetle) and clerid peak dispersal dates from yr-round traps, and dates of the actual southern pine beetle spring survey. The black bar represents the consecutive 4 wk period beginning with the median onset of dogwood bloom by yr and location. The dark gray bar represents the 4 consecutive wk that the annual southern pine beetle spring trapping survey was conducted. The light gray (southern pine beetle) and white (clerid) bars represent the consecutive 4 wk period during which the most beetles were trapped in yr-round traps. The percentages following the bars correspond to the percentage of southern pine beetle (black, dark gray, light gray) or clerid (white) spring trap captures from yr-round traps.

indicator of trap deployment resulted in missing 45% of the total *D. frontalis* spring dispersal, whereas in the worst case 92% of the spring dispersal passed before dogwood bloom. This suggests that historical timing of trap deployment could at least explain some of the recent inaccuracy with the annual spring survey. This also suggests that the survey's prediction model is based on deflated peak data, and improvements to timing of the survey will require the model to be recalibrated. The onset of eastern redbud bloom appeared a better phenological indicator of optimal *D. frontalis* spring survey timing. Our 2019 blooming survey indicated redbud bloom occurred 2.3 wk before dogwood bloom, narrowing the average 3 wk offset between *D. frontalis* peak dispersal and dogwood bloom measured in 2014 and 2015. However,

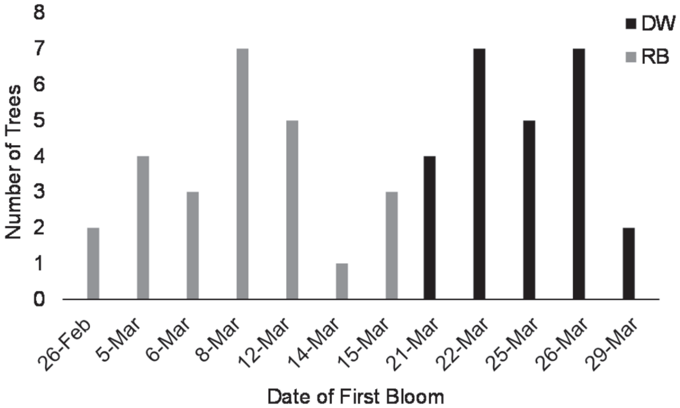

Fig. 2. The 2019 blooming dates of flowering dogwood (DW) and eastern redbud (RB) trees (*N* = 25 each) in an unmanaged woodlot on the periphery of the Thad Cochran Research, Technology & Economic Development Park at Mississippi State University, in Starkville, Mississippi, USA (33.475129°N, 88.793119°W).

eastern redbud bloom was variable highly among the trees monitored in 2019, creating the possibility of considerable asynchrony between onset of eastern redbud bloom and onset of peak *D. frontalis* dispersal.

Dogwood bloom may have historically coincided with peak *D. frontalis* spring dispersal, but scientific studies are lacking. If a correlation did once exist, climate change may have altered the phenology of both species (Davis et al. 2010). Dogwoods must be exposed to sufficiently cold temperatures for a long enough period before growth resumption can be initiated within the bud (Hunter & Lechowicz 1992). Once the chilling requirement has been met, bud burst occurs after exposure to a specific amount of thermal time above a temperature threshold has accumulated (Cannell & Smith 1986), which can result in bud burst occurring later in the spring after atypically warm winters occur. Conversely, *D. frontalis* may have as many as 8 overlapping generations per yr (Hain et al. 2011). They overwinter in all life stages and continue to develop even at 0 °C (Lombardero et al. 2000). Adults may emerge and disperse after a few unseasonably warm d in the winter and early spring (Moser & Dell 1979). Cold winters should promote a synchronous spring emergence, particularly in the northern portion of the range of *D. frontalis* and higher elevation pine forests (Lombadero et al. 2018). Warmer winters result in staggered emergence as was observed in our study in southern states. Climate change likely will increase instances of multimodal spring emergence by *D. frontalis*, complicating the use of any phenological indicator for survey timing and continuing to impact the accuracy of the prediction model.

One method to overcome increased variability in *D. frontalis* spring emergence would be to extend the trapping period beyond the current 4 wk standard. Our results indicate that 6 wk of trapping, the maximum recommended life of the lures, only slightly would improve the chances of capturing peak emergence or the presence of multimodal emergence. Trapping for longer than 6 wk would add additional cost and require increased labor for trap collection and beetle counting. Therefore, the practicality of using longer trapping periods is minimal. Another technique would be the development of a robust model designed to determine optimal survey start dates based on weather conditions and thresholds of *D. frontalis* developmental and flight temperatures. Degree d models usually are good candidates for such models because they can successfully predict key life history events for insects depending on weather conditions. The potential winter emergence of *D. frontalis* would make selecting a biologically meaningful time to begin accumulating degree d for *D. frontalis* difficult. Another option would be to base the timing of the survey on *T. dubius* emergence. Their abundance in relation to *D. frontalis* numbers is an input in the prediction model, and our results suggest less variability in emergence patterns. The utility of this approach requires further study.

As discussed above, using a phenological indicator to time the surveys may be impractical due to variable emergence patterns driven by climate change. It is apparent from our results that survey trappers already are using factors other than dogwood or redbud bloom to deploy their traps (Fig. 1). The inconsistency in survey timing could possibly be explained by time constraints with other management duties such as timber harvests and prescribed burns. Trappers may have used historic trapping data for their region to help determine deployment dates. Local knowledge of climatic conditions and emergence patterns of *D. frontalis* may serve as the best source of determining when to begin the spring survey in the absence of a phenological cue.

In addition to issues of survey timing, recent problems in predicting *D. frontalis* outbreaks may be due in part to changes in the lure combination previously described. A recent study has demonstrated that the switch to the α- and β-pinene sleeve as the host component has reduced the trap catch of *D. frontalis* compared to using turpentine (unpublished data). More recently, an endo-brevicomin lure was included to synergize the attractiveness of the other 2 lures and enhance the survey's ability to detect low population levels of *D. frontalis*. Differences in the responsiveness of *D. frontalis* to these new lure components may explain the recent model failures partially. Recalibrating the model for the current lure scheme also could improve the predictive power of the survey.

The inclusion of endo-brevicomin also altered trap placement. Trap locations are now typically in hardwood inclusions within pine stands. Hardwood green leaf volatiles have been shown to significantly decrease *D. frontalis* trap captures (Dickens et al. 1992; Sullivan et al. 2007), thus the current displacement allows for more non-host species between the trap and preferred *D. frontalis* habitat. Changing trap locations frequently may affect survey results. Ideally trappers would examine trap catches annually and relocate traps from sites that historically collected very few *D. frontalis* even when population levels are moderate to high. Establishing and continuously using reliable trap sites would provide consistency in the survey and aid in recalibrating the model to improve the validity of the results. However, maintaining the same sites from yr to yr often is confounded due to turnover in staff and landscape changes from management activities, storm events, etc.

Given the uncertainty in survey timing, revising the prediction model to include climate data could help improve the model accuracy back to previous standards. A forecast system using weather and stand data, previous yr infestation levels, and a hydrological model to predict *D. frontalis* levels for a county has been developed (McNulty et al. 1998, McNulty 2019). Because an operational version of the model is a recent development, little information has been provided to potential users to date and the short- and long-term accuracy of the results have not been thoroughly evaluated. Perhaps a combination of the 2 prediction methods may serve to improve the overall ability of forest managers to anticipate and prepare for outbreaks.

The spring survey is an integral part of the integrated pest management strategy for *D. frontalis*. In addition to helping predict seasonal infestation levels, survey results are valuable for preserving a historical record of *D. frontalis* population trends. The annual trapping also keeps foresters aware of the impacts of *D. frontalis* and the ecological and economic consequences of outbreaks. A better prediction system would provide additional justification for maintaining the survey. Our results indicate the following could help improve the efficacy of the prediction model: (1) shift trap deployment earlier than traditional dates, perhaps using eastern redbud bloom as a cue; (2) include local

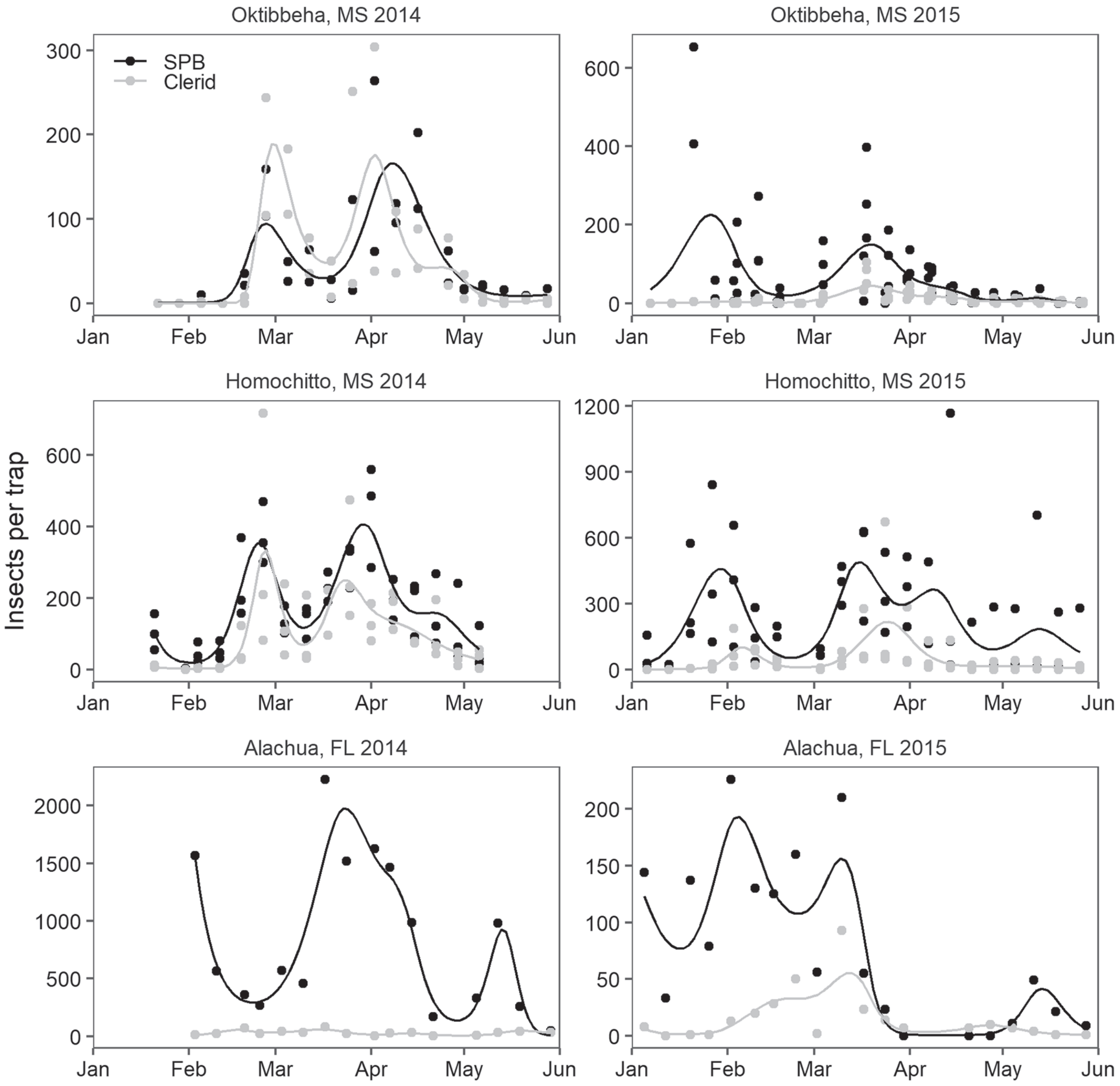

Fig. 3. Southern pine beetle (SPB) and checkered clerid beetle spring trap captures from yr-round baited Lindgren funnel traps. For each site by yr combination, number of beetles captured per trap was analyzed as a smooth function of survey wk using a generalized additive model (GAM) to show peaks in capture data. Black lines are fit GAMs for southern pine beetle, whereas gray lines are the fit GAMs for clerid beetle. Produced using Poisson distributions and log link functions with the mgcv package (Wood 2011) in R statistical software (R Core Team 2020).

knowledge to determine when the trapping period should occur; and (3) incorporate climatic data with trap catch numbers in the model.

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