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Spatial distribution and movement patterns of stored-product insects

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Abstract

If the foundation of an effective pest management program is an understanding of pest ecology and behavior, then this understanding must be at an appropriate spatial and temporal scale for the pest species and the environment. This is because the structure of the landscape mosaic in which an organism lives influences ecological processes such as population dynamics, movement patterns, and spatial distribution. Stored-product pests occupy spatially and temporally fragmented landscapes that can have profound impacts not only on their population dynamics, but also our ability to monitor populations and effectively target pest management. Recent research findings regarding these broader landscape issues in relation to stored-product pest spatial distribution and movement patterns will be presented. The focus will be on *Rhyzopertha dominica*, the lesser grain borer, temporal and spatial patterns in flight activity and dispersal, and the influence of land-cover and land-use patterns on flight activity. How this data has generated new hypotheses about the ecology and behavior of this pest and provided insight into more targeted pest management approaches will also be discussed.

Key words: Behavior, ecology, landscape, *Rhyzopertha dominica*, lesser grain borer.

Introduction

The importance of landscape structure and how organisms interact with spatial and temporal landscape heterogeneity has come to the forefront of ecology, and this perspective is making inroads into pest management as well. If, as it has been argued, the foundation of an effective integrated pest management (IPM) program is an understanding of pest ecology, then this understanding needs to be developed within the appropriate landscape structure and at the appropriate scale for that pest. This may be especially true for post harvest IPM, where the focus on sanitation, structural modification, and targeted pest control tactics can be summarized in ecological terms as manipulating the landscape structure to make it less favorable for pest population establishment, growth, and persistence.

Environments created or modified by humans tend to be highly fragmented landscapes consisting of a mosaic of resource patches that are separated from each other by barriers to movement or by a matrix of less hospitable habitat (Wiens, 1976). Landscape structure and dynamics influence ecological processes (e.g., population dynamics, spatial distribution) of the organisms living in the landscape (Turner, 1989; Wiens, 1976; Wiens et al., 1993). For example, spatial heterogeneity affects individual movement behavior, which in turn influences dispersal success and the distribution and persistence of populations (With and Crist, 1995;

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With et al., 1997). Populations can be made up of interconnected subpopulations occupying different resource patches [metapopulations (Hanski and Simberloff, 1997)], and the degree of movement among patches is what defines the type of metapopulation structure and the scale at which individuals can be considered to be from the same population. Through its influence on resource patches (size, number, and distribution) and the movement of organisms, landscapes structure can have important influences on metapopulations. When there is considerable movement among patches and population trends within patches are correlated with each other, this is considered just a single patchily distributed population; but, as the level of recruitment from within a patch increases relative to immigration from other patches, the population becomes more of a true metapopulation (Harrison and Taylor, 1997). A range of intermediate scenarios may be especially relevant to stored-product insects, particularly source-sink metapopulations where populations in higher quality (source) patches persist and produce individuals that immigrate into lower quality (sink) patches and enable subpopulations to persist in these less favorable locations. Only recently have metapopulation models begun to take into account the spatial structure of the landscape (DeWoody et al., 2005), and stored-product insects have served as useful models (Bancroft and Turchin, 2003).

It can be argued that stored-product pests of the grain and food industries are pests in large part due to their effectiveness at finding and exploiting the temporally and spatially fragmented landscapes within food facilities and within which food facilities are located. Targeting pest management to locations where pests are present can increase the probability of suppressing the pest population, and reduce the cost of management and risk of negative nontarget consequences (Brenner et al., 1998). In evaluating treatment efficacy, it is important to consider the spatial scale over which pest subpopulations interact, because this determines the proportion of individuals exposed to treatment and the potential for recolonization. For example, when pest subpopulations are interacting over spatial scales larger than an individual structure, rapid pest resurgence after treatments are applied to that structure could occur due to recolonization from other source patches. Broad spatial scale processes may be driving population dynamics within food storage and processing structures, but for most stored-product pests, with the notable exception of *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) (Hill et al., 2002), our understanding of ecology and behavior at broader landscape scales is limited.

Multiple studies have found that stored-product insects have spatially and temporally patchy distributions inside structures (Arbogast et al., 2000; Arbogast et al., 1998; Campbell et al., 2002; Nansen et al., 2004), and even around the outside of structures (Campbell and Mullen, 2004). Although studies measuring stored-product insect dispersal ability are limited, they indicate that many stored-product insects are highly mobile and capable of moving among food patches (Campbell and Arbogast, 2004; Campbell et al., 2002; Chesnut, 1972; Fadamiro, 1997; Hagstrum and Davis, 1980). Stored-product pests are often trapped outside grain storage and processing structures (Campbell and Arbogast, 2004; Campbell and Mullen, 2004; Doud and Phillips, 2000; Dowdy and McGaughey, 1994; Fields et al., 1993; Throne and Cline, 1989, 1991) and sometimes far away from these structures (Cogburn and Vick, 1981; Sinclair and Haddrell, 1985; Strong, 1970; Vick et al., 1987), which suggests the capability for long distance flight. However, these captures may also indicate localized movement of feral populations. Studies have also shown that insects can immigrate into facilities (Campbell and Arbogast, 2004; Campbell and Mullen, 2004; Hagstrum, 2001). These patterns suggest the potential for stored-product insects to be interacting with broader landscape patterns than just those inside food facilities.

A variety of approaches can be taken to study the influence of landscape structure on stored-product pest spatial distribution and movement. For some species, locations and questions, fine scale spatial patterns may be most important in impacting movement and distribution. For investigation of these patterns, field studies can be performed and, as discussed above, many studies of pest distribution within food facilities have shown temporally and spatially patchy distributions. Another approach that can be used is to create experimental landscapes in which the influence of landscape features on behavior and ecology can be examined in more detail. Studies of animal movement on these landscapes can provide insight into the relevant spatial scale, and ultimately into how organisms perceive landscape structure and the scale(s) at which they interact with spatial complexity (With, 1994). The experimental landscape approach has been used for stored-product insects (Bancroft and Turchin, 2003), and a number of current research projects are exploring the impact of landscape structure on red flour beetle behavior and ecology. However, many stored-product species are likely to interact with landscape structure over much broader spatial scales then can be fully understood in the laboratory. This seems to be the case for the *P. truncatus* (Hill et al., 2002) and may also be the case with its relative the lesser grain borer, *Rhyzopertha dominica* F. (Coleoptera: Bostrichidae). Here, some recent research findings on *R. dominica* are presented to show how these broader landscape issues might be important in understanding and managing this pest.

Rhyzopertha dominica is a devastating cosmopolitan pest of stored grain, grain products, and other materials (Potter, 1935). There is little evidence that *R. dominica* infests wheat in the field (Hagstrum, 2001). Therefore, infestation in storage results from either a failure to remove residual populations from storage structures or from dispersing individuals finding and exploiting stored grain. *Rhyzopertha dominica* is a strong flier that is commonly captured near grain elevators and farm storage bins (Dowdy and McGaughey, 1994, 1998; Edde et al., 2005; Throne and Cline, 1991), but also far away from farm storage structures (Edde et al., 2005; Fields et al., 1993; Sinclair and Hadrell, 1985). There is also some evidence suggesting that *R. dominica* can survive in the wild on other hosts such as wood twigs and acorns (Potter, 1935; Wright et al., 1990). The relative importance of these sources is not well understood, but generally regarded as low. Hagstrum (2001) showed that *R. dominica* can immigrate into grain bins through the eaves, vents, and poorly sealed bin bottoms. There is limited information on long-term outdoor monitoring of *R. dominica* around grain storage facilities (Dowdy and McGaughey, 1998; Throne and Cline, 1991).

To investigate broader landscape scale questions about *R. dominica* populations in Kansas, we addressed the following questions. First, how far is this species capable of dispersing in the field? This would provide an estimation of the spatial scale over which landscape features might be interconnected. Second, how patchy is the distribution of beetles within the landscape and what are the important landscape features that impact spatial distribution? Beetle spatial distribution may by influenced primarily by the grain storage sites on the landscape or by other landscape features. The family Bostrichidae contains many species of wood borers that are associated with forests and the other major stored-product pest in this family, *P. truncatus*, has been found to be attracted to wood, to feed and reproduce on certain types of wood, and to be associated with forests habitats in some parts of the world (Hill et al., 2002). Forested areas in an agricultural landscape may also contribute to the spatial mosaic of resource patches for *R. dominica*. Finally, how important are these broader landscape patterns in flight activity in terms of impacting populations within food facilities?

Dispersal capability of *R. dominica* in the field (Ching'oma, 2006)

Materials and methods

Mark-release-recapture studies in the field were used to assess the dispersal ability of *R. dominica* adults. Releases were conducted in a native tallgrass prairie landscape in Kansas USA that previous studies have shown contains *R. dominica*, but in which there was no grain production or storage. Beetles for release were collected from the field within the previous year and, after the first generation, reared under conditions that have been previously demonstrated to maximize flight initiation (Perez-Mendoza et al., 1999).

Releases were made in the center of a circular grid (radius of 1 km) of four-funnel Lindgren traps (Phero-Tech. Inc., British Columbia, Canada) containing a *R. dominica* aggregation pheromone lure (Trécé, Inc., Adair, OK USA). Traps were placed at various distances from the center release point (Turchin and Thoeny, 1993). Prior to release, adults were marked so that recaptured beetles could be identified. Beetles were released approximately two h before sunset. In 2003, 15,900 marked beetles were released over two release dates (27 August and 16 September). In 2004, 44,820 beetles were released over seven dates in June. Traps were checked at different time intervals depending on the release date. All collected beetles were inspected for the presence of the marking agent and assigned to a release date or classified as feral beetles.

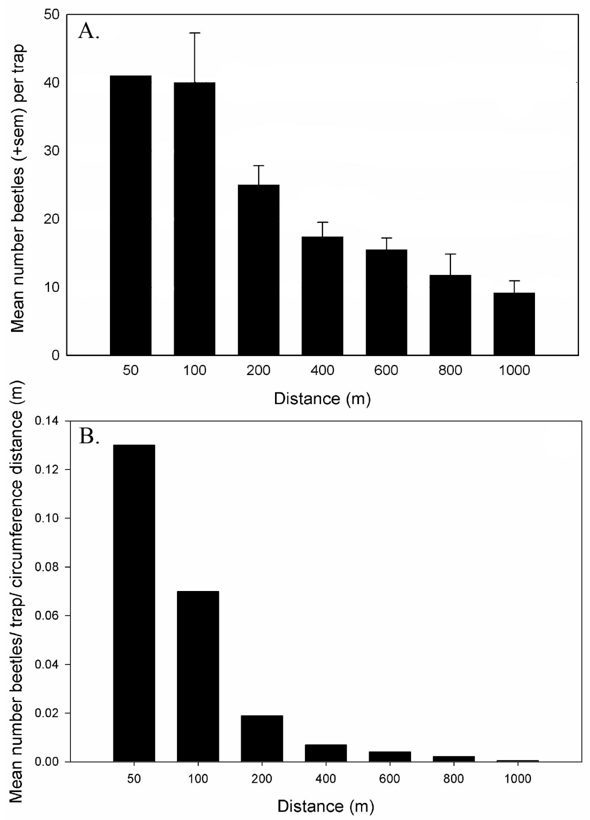

Figure 1. (A) Mean (+ SEM) number of lesser grain borers, *Rhyzopertha dominica*, recaptured (n = 872) at various distances at Konza Prairie, Kansas, for all releases in 2003 and 2004. (B) Mean number of beetles per trap adjusted for circumference distance (m) between traps at different radii from release point.

Results

The average dispersal distance of recaptured beetles over all the release dates combined (n = 872) was 380.4 ± 10.5 m and ranged from the minimum to the maximum trap distance of 1,000 m (Figure 1). There was no difference between the sexes in dispersal distance in either 2003 (t-test: t = 0.78, df = 36, P = 0.44) or 2004 (t = 0.23, df = 410, P = 0.23). Diffusion coefficients ranged from 102.7 to 172.8 m/day for beetles captured in the first four d after release during which over 80 % of beetles were recaptured. Some beetles were recaptured 1 km away from the release point within one (n = 1) or two d (n = 11). Marked beetles were also captured in sticky traps placed outside the recapture grid at distances up to 3.6 km from the release point.

Impact of landscape features on spatial distribution of *R. dominica* in an agricultural landscape (Ching'oma, 2006)

Materials and methods

Flight activity was monitored in an agricultural landscape in central Kansas USA that contained a mosaic of agricultural fields (primarily wheat, corn, and sorghum); pasture; woodland; farm, residential, and commercial buildings; grain storage bins; and a county grain elevator. Beetle flight activity was monitored between May and November 2003 and April and November 2004 using a grid of 203 Delta sticky traps (Scentry Biologicals Inc., Billings, MT USA) baited with pheromone lures. Traps were evenly spaced along roadsides within a 10.7 by 9.3 km area, with traps also placed on farms with steel bins for storing wheat. The geographic coordinates of all pheromone trap locations and all grain storage bins within the monitoring area were recorded. Traps were replaced at approximately two-week intervals and returned to the laboratory to count the number of trapped beetles.

Temporal patterns in spatial distribution were evaluated for each year. Spatial autocorrelation of number of beetles captured on trap locations was assessed by computing Moran's I Index. Contour maps using Inverse Distance Weighting (IDW) for number of beetles captured in traps were developed using the Geostatistical Analyst extension in Arc GIS 9.1 computer software (ESRI, Redlands, CA). As an indirect method of quantifying dispersal, ellipses around the calculated mean center distribution that encompassed 60 % of total number of beetles captured were calculated in Arc GIS 9.1.

The influence of grain storage structures on *R. dominica* distribution in the landscape was analyzed using two approaches. First, for the eight monitored farm bin locations, the number of beetles captured in the traps within 5 km radii of the farm locations was regressed against the distance from the farm bins. Second, to extend the evaluation to all storage locations in the study area, pheromone trap locations were sorted by the number of farm bin locations within a 1 km radius of the trap and the average number of beetles captured was calculated and compared using PROC GLM (SAS Institute, 1999).

An analysis of the impact of landscape features on the number of beetles captured was performed using the Spatial Analyst feature in ARC GIS 9.1. A national land cover database (NLCD) and land use raster map (USGS, 1992) covering the study area was imported as a data layer. The tabulate area option was used to create circle polygons around trap locations, and the area of the various land use types within 100, 500, and 1,000 m radial distances from each trap location were calculated. These areas were converted to percentages, and the effect of the percentage land use on total number of beetles captured for each year was assessed using stepwise regression (SAS Institute, 1999).

Results

The seasonal patterns of insect captures in both years indicated there was an early season flight peak, and, in one of the two years, a late season flight peak occurred (Figure 2A). In 2003 and 2004, Moran's I values ranged from 0.01 to 0.16, indicating significant positive spatial autocorrelation in trap captures. In 2004, trap captures during the first flight activity in the spring (15-29 April) were clustered near the center of the landscape, with most of the landscape, particularly in the eastern half having low trap captures (Figure 2B). In the previous year (2003) the pattern was similar, but trapping started

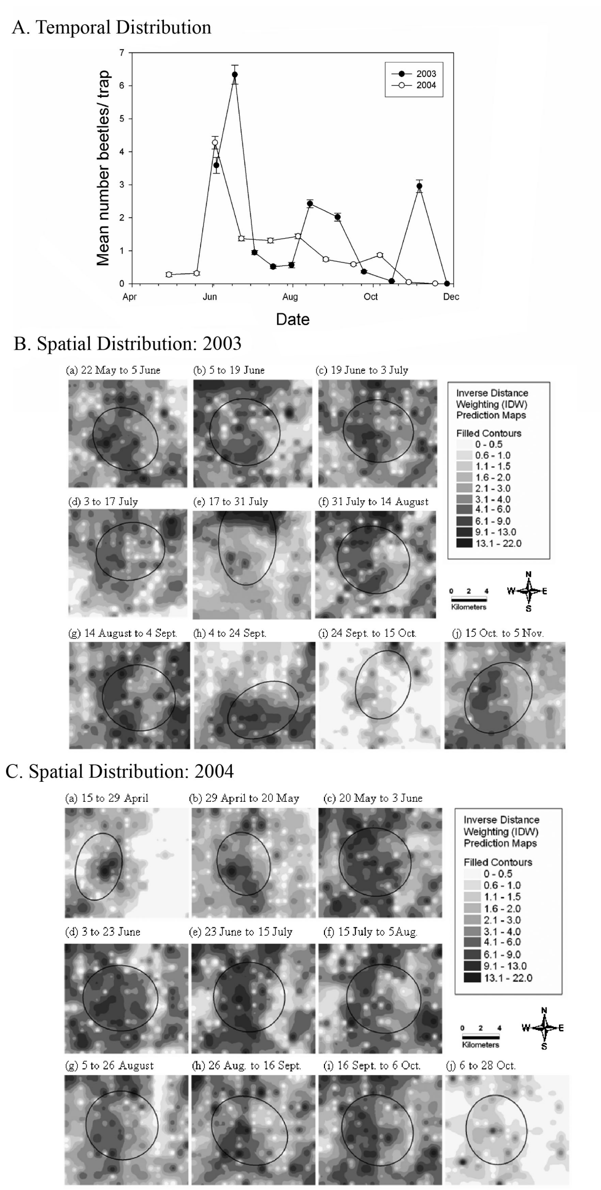

Figure 2. (A) Mean (± SEM) number of lesser grain borers, *Rhyzopertha dominica*, captured in 2003 and 2004. (B) Contour maps (Inverse Distance Weighting) of trap captures in the study area for each sampling interval in 2003 and (C) 2004. Ellipses on contour maps indicate area in which 60 % of the beetles were captured and are centered on the calculated mean center of distribution.

later in the spring so that the initial foci of flight activity was missed. Interestingly, these early season trap captures tended to occur in traps in or near a forested riparian area, not near farm locations. By the late May to early June sampling periods, the numbers captured had increased across the whole landscape, but this was occurring before wheat was harvested and stored (late June to early July) and when most farm storage bins were likely to be empty. Trap captures stayed relatively high and widely distributed throughout the season, until dropping in Oct to a few scattered hot spots. In 2003, in the fall after an initial drop in number captured per trap on 24 Sept to 15 Oct (as observed in 2004) a large late season flight occurred during the 15 Oct to 5 Nov sample period.

The hypothesis that beetle captures would tend to be associated with grain storage sites was not supported by the data from either 2003 or 2004. If beetles tend to be associated with grain storage, it was hypothesized that trap captures should decrease as distance from bins increased. However, linear regression of trap captures with distance for each sampling interval indicated that for most locations and sampling periods there was not a significant linear relationship. When the model was significant, trap captures tended to increase with distance (31 out of 136 location/sampling period combinations), rather than decrease with distance (3 out of 136 location/sampling period combinations). The number of farm bin locations within 1 km of trap locations ranged from 0 to 4, but there was no significant difference in total beetle captures among trap locations with different numbers of bins in the vicinity of the trap in either 2003 (GLM: $F = 0.96$, df = 4,196, $P = 0.43$) or 2004 ($F = 1.66$, df = 4,196, $P = 0.16$).

To determine the influence of other landscape features on trap captures, stepwise regression was performed and three different radii around the traps was tested because it was not known *a priori* the spatial scale of any landscape influence. Percentage deciduous forest area was the most significant landscape feature affecting the total number of beetles captured for the combined data and for most of the individual sampling intervals in each year. More beetles were captured with increasing percentage deciduous forest area within all three size circles around trap locations in 2003 (100 m: $F = 27.03$, $P < 0.01$, $R^2 = 0.12$; 500 m: $F = 35.84$, $P < 0.01$, $R^2 = 0.16$; and 1000 m: $F = 23.47$, $P < 0.01$, $R^2 = 0.11$) and 2004 (100 m: $F = 29.16$, $P < 0.01$, $R^2 = 0.13$; 500 m: $F = 47.04$, $P < 0.01$, $R^2 = 0.19$; and 1000 m: $F = 33.33$, $P < 0.01$, $R^2 = 0.14$). Other prominent landscape features such as pasture/grassland, row-crop land, water, and residential land were not significant in the stepwise regression.

Impact of broader landscape pattern on flight activity and population dynamics within food facilities (Toews et al., 2006)

Materials and methods

In and around a Foundation seed warehouse located at Manhattan, Kansas USA, Lindgren traps were placed in cardinal directions at distances of 0, 50, 100, and 150 m from the warehouse and three additional traps among the grain bins. Two Lindgren traps and six Storgard II sticky traps (Trécé Inc., Adair, OK, USA) were placed inside the warehouse. All traps were baited with *R. dominica* pheromone lures. Indoor traps were serviced weekly and outdoor traps were serviced each weekday from late April through November 2004. To identify potential routes of entry into the warehouse, small gaps between warehouse overhead doors and the doorjamb were monitored using unbaited glue boards (Trapper® MAX, Bell Laboratories Inc., Madison, WI, USA). Traps were fastened to the interior side of the doorjamb such that insects moving through the gap might become trapped. For each of two overhead doors, on each side of the door one trap was placed flat on the floor and ten successive traps were placed one above the other to a height of 200 cm from the ground, and three additional traps were placed along the top of the door. Sticky traps were replaced at least monthly depending on trap condition. Indoor *R. dominica* captures in pheromone traps and on unbaited glue boards were related to mean outdoor captures by week using correlation analyses (SAS Institute, 1999).

Results

Distinct seasonal peaks in *R. dominica* captures outside were observed, with a large spring peak in early and mid-May and then the rate of captures tailed off to a fairly consistent level between 1 June and 15 August. From late August through October relatively large numbers of captures were recorded intermittently before ending in mid-November. A significant effect attributed to trap distance from the warehouse was observed in the north-south transect ($F = 7.00$, df = 1,285; $P < 0.01$) and in the east-west transect ($F = 6.70$, df = 1,285; $P = 0.01$): captures increased with distance from the warehouse.

Although fewer *R. dominica* were captured inside the warehouses than outside, the trends were similar to those of outdoor traps. There was a strong positive correlation between mean outdoor captures and indoor captures in Lindgren traps ($r = 0.99$, $P < 0.01$; $n = 28$) and in Storgard II traps ($r = 0.97$, $P < 0.01$; $n = 28$). Captures of stored-product Coleoptera on unbaited glue boards positioned adjacent to overhead doors suggest that this is an important route of entry for insect infestations. The temporal distribution of *R. dominica* captures on unbaited glue boards was highly correlated with weekly capture of *R. dominica* in outdoor pheromone-baited traps ($r = 0.92$, $P < 0.01$; $n = 27$). More than three times the number of *R. dominica* were captured at floor level than all other locations combined.

Discussion

Our understanding of the influence of landscape structure on stored-product insects is still limited, but results reported here illustrate how broader scale temporal and spatial patterns may have a strong influence on pest populations. For the highly mobile pest, *R. dominica*, in the agricultural landscape in Kansas USA presented here, we originally hypothesized that beetles would be primarily associated with grain storage sites and the importance of pest immigration into bins would depend on dispersal ability and the distance to surrounding infested storage locations. Our findings did not support this hypothesis, but instead suggest that depending on the time of year beetles are active across the whole landscape and deciduous woodlands may be strongly influencing beetle distribution patterns. Woodlands may be an important reservoir for pests moving into grain storage by serving as an alternative resource patch in which they reproduce and/or as overwintering sites. Because pheromone trapping data is an indirect measure of pest populations and influenced by a range of factors, at this point we do not know if either of these hypotheses is supported, or if trap captures are being influenced by some other confounding factor(s). Peaks of trap captures in the fall and spring, raise the possibility that beetles have a dispersal phase prior to overwintering and that they could be overwintering in non-grain storage habitats and this may serve as a source of beetles to infest newly stored wheat in the spring. It is likely that different patterns of spatial distribution, movement, and population structure will occur in other landscapes, in other geographic areas, and certainly with other pest species. Understanding these processes could help in the implementation and interpretation of monitoring programs and the selection and targeting of pest management tactics to make IPM programs more effective.

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