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Population dynamics of stored maize insect pests in warehouses in two districts of Ghana

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ABSTRACT

Understanding what insect species are present and their temporal and spatial patterns of distribution is important for developing a successful integrated pest management strategy for food storage in warehouses. Maize is stored in bags in warehouses in many countries in sub-Saharan Africa, but little monitoring information is available on insect activity in those warehouses. We monitored the populations of major post-harvest insect pests of maize at three different warehouses (MiDA, Gundaa and Wienco) in two regions in Ghana (Middle Belt and Northern Belt). The study was conducted from September 2015–July 2016, which represents a common maize harvest and storage period in the two regions. The most abundant insect pest found in the warehouses was *Plodia interpunctella* (Hübner), but other major pest species were recovered during the study. *Sitotroga cerealella* (Oliver) and *Prostephanus truncatus* (Horn) which are major pests on farms, were more likely to be captured in traps outside or at nearby farms than inside the warehouses. When recovered inside they tended to be found in the receiving and cleaning areas. *Sitophilus* spp. were commonly captured in the warehouses, but were more abundant in the Middle Belt warehouse. Our results identified the major species found during warehouse storage of maize in Ghana and suggest that the specific pest species may be different in warehouses compared to on-farm storage.

1. Introduction

Maize (*Zea mays* L.) is the most extensively cultivated cereal in the world and serves as a staple in many tropical, sub-tropical and warm temperate countries, including most parts of Africa (Onwueme and Sinha, 1991; FAOSTAT, 2014). Maize, together with rice and wheat, provides at least 30% of food calories to more than 4.5 billion people in developing countries (Shiferaw et al., 2011) and it is predicted that by 2050 demand for maize in the developing world will double (Rosegrant et al., 2009). Production of maize in Africa was estimated at ~37 million ha in 2014 (FAOSTAT, 2014). Maize storage and handling conditions in developing countries are often inadequate and farmers can experience large post-harvest grain losses (Jonsson and Kashweka, 1987; Boxall, 2001; World Bank, 2011). If processes such as threshing, drying and transporting are not properly conducted after harvest, grains can have a high moisture content and kernels can become cracked or broken. This can increase infestation by insects and fungi during storage, and lead to increased losses (Hodges, 2012). Accurate estimates of post-harvest losses are difficult to obtain, but a meta-analysis of post-harvest losses indicated that mean quantity losses for maize ranged between 5.6 and 25.5% (Affognon et al., 2015).

In the West African country of Ghana, maize is an important crop, with over one million ha harvested in 2014, and a production level of more than one million metric tons (FAOSTAT, 2014). The FAO GIEWS Country Brief for Ghana (2017) stated that 1.8 million metric tons were produced in 2016, an increase of 6% over the 2015 crop year. The Ministry of Food and Agriculture (2011) in Ghana estimated 84% of maize grown in Ghana is in the middle–southern region (Brong Ahafo, Eastern, and Ashanti regions), with the remaining 16% cultivated in the Northern Belt (Northern, Upper East, and Upper West regions). Smallholder, low-resourced, farmers

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produce maize under rain-fed conditions in most of the production zones in Ghana (Cordain, 1999; Ministry of Food and Agriculture, 2011). In Ghana, there are two maize crops per year in the middle-southern region (major and minor seasons) and one crop per year in the Northern Belt. Danso et al., (2017) found that generally more insect infestations occurred during the minor season in the middle-southern region than during the major season, but that aflatoxin levels were higher in the major season. After harvest, maize can be stored at the smallholder farmer level or it can follow a chain of post-harvest operations as it moves from the field to storage in warehouses before distribution to the final consumer. Losses in quantity and quality can occur all along this chain, with Danso et al. (2017) finding insect infestations occurring in the field before harvest and when piled after harvest, but generally decreasing after the grain is dried and ready for storage. A survey by Amankwah (2009) indicated that most farmers in the Middle Belt of Ghana, a transitional zone that lies between the coastal and upland areas, use the traditional crib for dry-storage of maize after harvest, while others keep their maize in bags stored in their homes. Storage and transport of grain in sacks such as jute or polypropylene bags can be more practical and use has increased among farmers (FAO, 1994). Warehousing of bagged maize is also increasing in Ghana and this has the potential to improve the storage conditions by making it easier to inspect, treat, and distribute the grain.

There is little knowledge on insect activity at warehouses in Ghana even though this information is critical to understanding the potential for bagged maize to become infested with insects during warehouse storage. The main insect pests reported to attack stored maize in Ghana are the maize weevil, *Sitophilus zeamais* (Motschulsky) (Coleoptera: Curculionidae) and larger grain borer, *Prostephanus truncatus* (Horn) (Coleoptera: Bostrichidae) (Vowotor et al., 2005). In an evaluation of insects associated with maize from the field to post-drying stage in Ghana, Danso et al. (2017) found that *S. zeamais*, Angoumois grain moth *Sitotroga cerealella* (Oliver) (Lepidoptera: Gelechiidae), square-neck grain beetle *Cathartus quadricollis* Guerin-Meneville (Coleoptera: Silvanidae), and corn sap beetle *Carpophilus dimidiatus* Fabricius (Coleoptera: Nitidulidae) were the predominate species recovered. However, other reported insect pests that are damaging to stored maize in sub-Saharan Africa include the lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrichidae) and Indianmeal moth *Plodia interpunctella* (Hubner) (Lepidoptera: Pyralidae) (Midega et al., 2016) are also likely to be found in Ghana. Pheromone and kairomone baited traps can be used for monitoring pest insect activity and to guide pest management programs, although pheromone trap captures are relative estimates of abundance and efficacy of capture will depend on the trap and attractants used (Campbell et al., 2002).

Evaluation of factors responsible for post-harvest losses has focused on smallholder farm level activities, but with development of food distribution channels and warehouse storage there is a need for information on how to best manage losses and maintain quality throughout the value chain (Affognon et al., 2015). The objective of this study was to determine for the first time stored-product pest insect species associated with warehouse storage of maize and their seasonal patterns of abundance in the two maize growing areas in Ghana. We used pheromone or kairomone baited traps to evaluate insect activity. The data generated will provide baseline information on pest activity in and around warehouses to help in the improvement of management programs. This is part of a broader project to determine critical points of vulnerability to insect infestation in the maize distribution chain from the field to the final consumer in Ghana.

2. Materials and methods

2.1. Study sites

This study was conducted in two agro-ecological zones in Ghana — Ejura located in the Middle Belt of Ghana, between the coastal and upland areas, and Tamale located in the Guinea Savanna zone of Northern Ghana. Three warehouses were used in this study, one in the Middle Belt (MiDA, 1000-metric ton capacity) and two in Tamale (Gundaa, capacity of 500-metric ton, and Wienco, 3750-metric ton capacity). Maize was stored in the warehouses in polypropylene bags (PP) and jute bags in MiDA warehouses, PP bags in Wienco, and jute bags in Gundaa. The study was conducted from September 2015 to July 2016. In the Northern Belt, maize harvesting and processing typically occurs in December and January, with new harvest added to warehouses starting in late December. In the Middle Belt, there is a minor and major season crop of maize, with the minor season typically harvested between December and January, a similar timeframe with the Northern Belt, and the major season crop typically harvested between late July to early September. There is a delay between harvest and storage in the warehouses, while the maize is being processed and dried. The major season crop was not the focus of this study to facilitate comparison between the two regions in Ghana.

The three warehouses all had stacking rooms, where bags of grain were stacked on pallets, but the Gundaa and Wienco warehouses had receiving and cleaning rooms as well. In the MiDA warehouse, large quantities of major season grain were stored in the warehouse at start of the monitoring period and when new grain started to be added to the warehouse at the end of the monitoring period. In the Gundaa warehouse, there was only a small amount of grain left and carried over in the warehouse until the new maize from harvest was added in January 2016. Different cereal grains (millet, sorghum, and rice), legumes, and groundnuts were stored in the Gundaa warehouse until November 2015, when all the bags were removed. In the Gundaa warehouse, grain was stored in only the receiving and cleaning rooms, not the stacking room. The Wienco warehouse was empty at the start of the study and only started receiving new grain for storage in late December 2015. Although the Wienco warehouse had receiving and cleaning rooms, only the stacking rooms were used for storage.

Data loggers (UX100 Temp/RH, Onset Computer Corp, Pocasset, MA, USA) to record temperature and r.h. were installed in each warehouse. Data loggers were attached to walls of warehouses by hanging them on nails. Average temperature and r.h. over each monitoring period was calculated. Maize moisture content was not measured as part of this study, but information from markets in the region is available. In the Middle Belt maize moisture content content ranged between 8.52 and 16.5% from October to December 2015; between 8.8 and 12.1% from January to March 2016 and between 11.2 and 12.5% from April to June 2016 (JKD, unpublished data). In the Northern Belt maize moisture content in the markets ranged between 7.8 and 15.7% from October to December 2015; between 5.5 and 9.6% from January to March 2016; and between 8.8 and 11.6% from April to June 2016 (NM, unpublished data).

2.2. Pheromone traps

Two types of traps were used for monitoring stored-product insects. Storgard II traps baited with pheromone lures (Trece Incorporated, Adair, Oklahoma, USA) were used to monitor the populations of flying insect pests inside and outside the warehouses. The pheromone lures were for *S. cerealella, R. dominica, P. truncatus*, *P. interpunctella,* and red flour beetle (*Tribolium castaneum* (Herbst)) and confused flour beetle (*Tribolium confusum*

Jacquelin du Val). The five pheromone lures were placed in each trap, with each lure labeled with a marking pen to indicate the type of pheromone. Dome traps (Tréce, Adair, Oklahoma, USA) were also used for monitoring and were placed on the floor of the warehouses for capturing walking insects. Each Dome trap had an absorbent pad soaked in food based oil (kairomone) attractant and pheromone lure for *T. castaneum* and *T. confusum*.

2.3. Placement of traps in warehouses

2.3.1. Storgard II traps

Fifteen Storgard II traps were placed in the warehouses beginning on 11 September 2015 for the MiDA warehouse and 12 September 2015 for the Gundaa and Wienco warehouses. The MiDA warehouse had only a stacking room and all 15 traps were placed in that room. In the Gundaa warehouse, there were two smaller rooms which served as the receiving and the cleaning rooms and three traps were placed in each room, with remaining nine traps placed in the stacking room. The Wienco warehouse had 12 traps in the stacking room and three in the cleaning room. The traps in all warehouses were suspended using hangers on the wall at a height of 1.83 m from the floor, and aligned so that open ends of the traps did not face the wall to facilitate entry of insects and improved air movement through traps.

At each warehouse, additional traps were placed outside the warehouse, along the perimeter of the warehouse property, and for two warehouses additional traps were placed at nearby farms, to determine the level of insect activity in the landscape around the warehouses. Six Storgard II traps were placed outside the warehouses starting in December 2015 and were hung 1.83 m high on the fenced-walls around the warehouses. An additional five Storgard II traps were placed at maize farms 300 m and 500 m from the MiDA and Wienco warehouses, respectively, starting in June 2016. The traps were hung on farms at the same height as the maize present in the field, which were selected at random. The nearest farm was more than 1000 m from the Gundaa warehouse, so no farm traps were placed at this warehouse.

2.3.2. Dome traps

Dome traps were deployed on 25 January in the MiDA warehouse and 26 January in the Wienco and Gundaa warehouses. The number of traps placed in the MiDA, Gundaa and Wienco warehouses was 12, 15 and 18 traps, respectively. The traps were placed on the floor adjacent to the wall and about 6 m apart from each other in the warehouses.

2.4. Data collection and servicing traps

Traps were checked every two weeks (first data collection from Storgard II traps on 11 October 2015) and the number of each species found was counted and recorded. All data reported is the average number captured per trap over this two-week period. Records were kept on dates when the traps were deployed and inspected. Insects trapped on the sticky surfaces of the traps were removed using a pair of forceps and counted. For each trap in each warehouse, the number of insects of each species was recorded. When sticky surfaces of Storgard II traps were 50–60% covered with dust and/or insects, they were replaced. Prior to replacing traps, pheromone lures were removed and transferred to new traps and lures were replaced every three months. In the case of the Dome traps, every two weeks the absorbent pad and kairomone oil in the catch reservoir of each trap were removed, the trap cleaned, and a new absorbent pad and kairomone placed in the catch reservoir as previously described.

3. Results

3.1. Pattern of stored product insect captures at warehouses

3.1.1. Middle Belt, MiDA warehouse

In the MiDA warehouse, pest management tactics during the monitoring period were limited; a cleaning of the warehouse was performed on 23 April 2016, but bags of maize were not fumigated and no aerosol insecticide treatment was performed during the monitoring period. Relative humidity in the warehouse was at its lowest in January and February, with a trend upward from February through July, and temperatures were at their highest between February and April (Fig. 1A).

Insect captures in Storgard II traps inside the warehouse were low throughout the monitoring period, except for *P. interpunctella* which increased in May 2016 and remained high, averaging more than 35 moths per trap, until the last month of data collection in July (Fig. 1B). This increased activity occurred as r.h. increased and temperature decreased. Other species captured at low numbers were *S. cerealella*; mean numbers captured ranged up to 1.0 insect/trap, and *P. truncatus,* mean numbers captured ranged up to 0.2 insect/trap.

Inside the MiDA warehouse, *Sitophilus* spp. and *T. castaneum* were routinely captured in Dome traps (Fig. 1C), but not in the Storgard II traps. *Sitophilus* spp. is used because both *S. zeamais or Sitophilus oryzae* can be found infesting maize and external morphology is similar for both species, making separate of species difficult. *Sitophilus* spp. were captured throughout the monitoring period in this warehouse, except for a two-month period in April and May 2016 when no individuals were captured. *T. castaneum* was captured at similar levels throughout the monitoring period. In February and March, single *R. dominica* adults were captured in Dome traps. Other incidental insects captured in Dome traps were ants, which were not identified as they were not considered to be stored product insect pests.

Insect captures outside the MiDA warehouse showed that *P. interpunctella* was the most abundant species throughout the monitoring period (Fig. 1D). There was a high mean capture of 15.8 ± 5.6 insects/trap on 11 March, even though during this period few were captured inside the warehouse. Later in the monitoring period when captures inside the warehouse were high, they were still regularly captured in the outside traps. Low numbers of *S. cerealella, P. truncatus,* and *R. dominica* were also captured throughout the monitoring period and low numbers of *T. castaneum* were captured in March and April. Average captures for these other species never exceeded two insects per trap, and typically the average was less than one per trap.

3.1.2. Northern Belt, Gundaa warehouse

In the Gundaa warehouse, pest management tactics during the monitoring period included cleaning on 23 January and 24 June 2016, and a fumigation with phosphine performed on 22 July 2016 prior to the last day of data collection. Temperature was relatively high throughout the monitoring period (>30 °C), except for a period in July when it dropped closer to 25 °C, and r.h. was at its lowest between December and February, and then increased until the end of the monitoring period (Fig. 2A).

Inside the warehouse, *P. interpunctella* was captured in the Storgard II traps throughout the monitoring period and had the

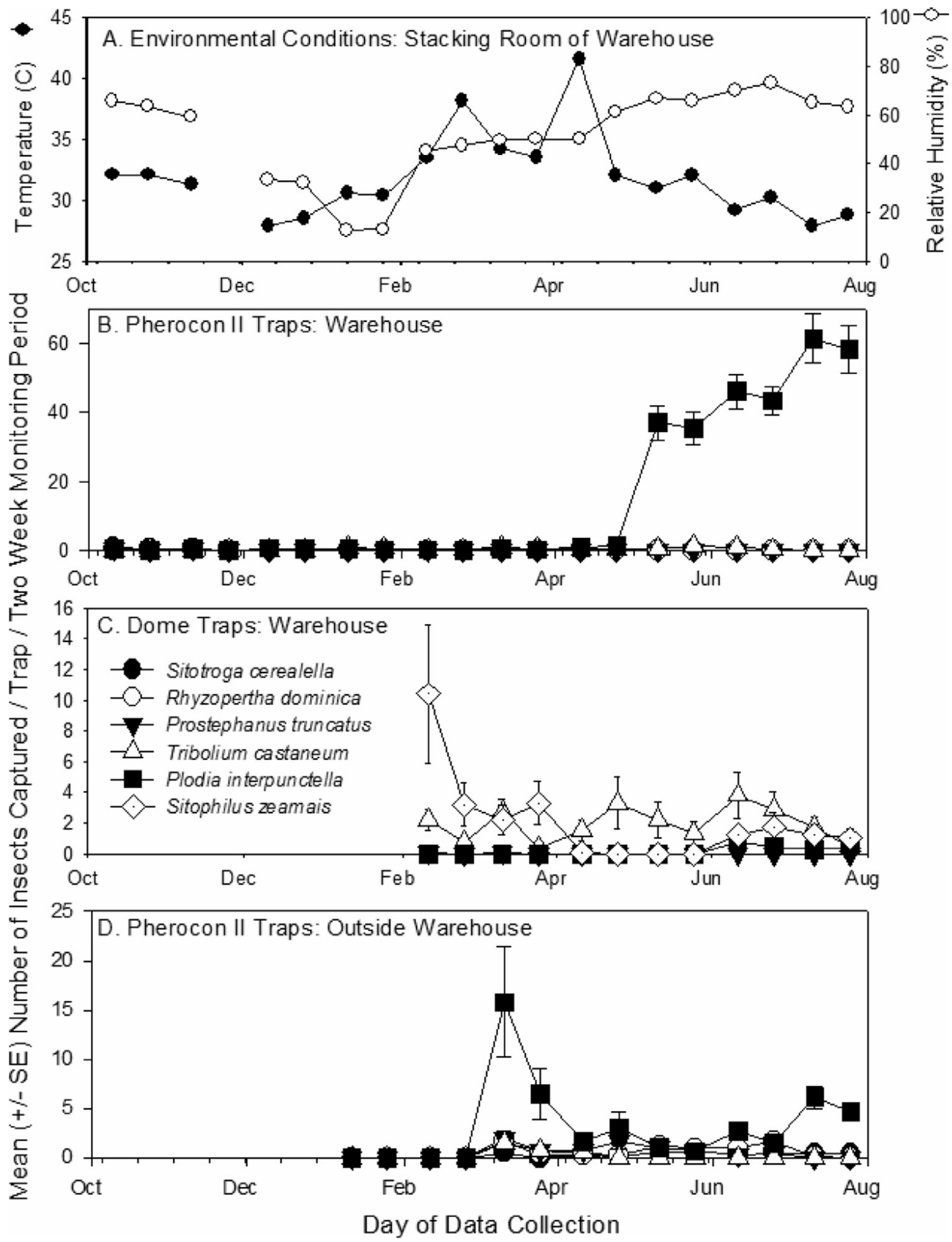

Fig. 1. MiDA warehouse, Middle Belt of Ghana, temperature and r.h. in stacking room of warehouse (A), and mean (±SE) number of insects captured/trap in the preceding two-week monitoring period in Storgard II traps placed in warehouse (B), Dome traps placed in warehouse (C), and Storgard II traps placed outside the warehouse (D).

highest average captures (maximum average capture of 27.7 ± 6.7 insects/trap) in March (Fig. 2B). Traps in the receiving and cleaning rooms, where the maize was stored, had higher moth captures in a trap compared to the stacking room. The spike in activity in March was due to high moth captures in all the receiving and cleaning room traps (average of 57.5 ± 4.1 and 57.5 ± 7.2 insects/trap for the March sampling periods), with stacking room moth captures remaining relatively low (average of 7.8 ± 0.7 and 3.9 ± 1.0 insects/trap for the March sampling periods). *S. cerealella* was captured primarily in October and November period, and was not captured again inside this warehouse after December (except for one moth captured in the sample from 11 February 2016) (Fig. 2B). This activity corresponded with the time prior to adding maize to the warehouse and when millet, sorghum, rice, legumes, and groundnuts were removed from the warehouse in November. One *R. dominica* adult was captured on the first sampling date, *P. truncatus* was captured primarily in October and November, and *T. castaneum* was captured throughout the monitoring period, but for all these species the average captures were typically ≤1 beetle/trap.

In the Dome traps, *T. castaneum* was the most prevalent species captured, and were captured during all but one monitoring period (Fig. 2C). *Sitophilus* spp. were also captured during three monitoring periods in March and April, but none were captured during the rest of the monitoring period. Captures of *P. interpunctella* and *R. dominica* were in the Dome traps over the entire monitoring period was very low, only one of each species over the whole monitoring period.

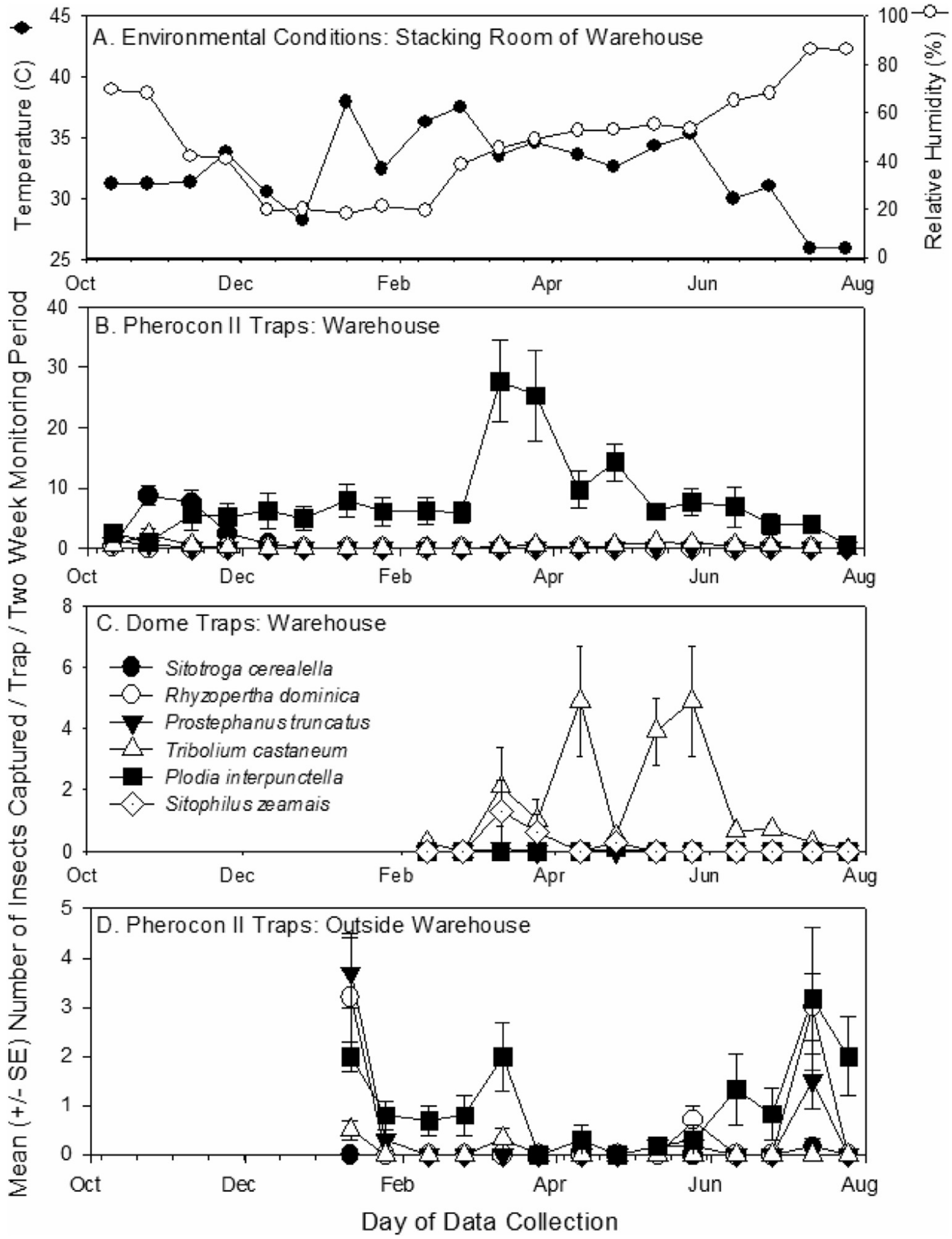

Fig. 2. Gundaa warehouse, Northern Belt of Ghana, temperature and r.h. in stacking room of warehouse (A) and mean (±SE) number of insects captured/trap in the preceding two-week monitoring period in (B) Storgard II traps placed in warehouse (B), Dome traps placed in warehouse (C), and Storgard II traps placed outside the warehouse (D).

In traps placed outside the warehouse, low numbers of all targeted insect species were captured (Fig. 2D). Both *P. truncatus* and *R. dominica* were captured more regularly outside than inside the warehouse. *P. interpuntella* was captured outside at almost all monitoring periods throughout the year, and although it was often the most abundant species captured outside it was captured at lower levels than in traps placed inside the warehouse. Except for *P. interpunctella*, outside insect captures tended to be lowest between February and May.

3.1.3. Northern Belt, Wienco warehouse

In the Wienco warehouse, pest management tactics during the monitoring period included cleaning of the receiving and cleaning room on 25 October 2015 and on 20 January and 25 April 2016, and cleaning in the stacking room on 11 November 2015. Insecticide treatments using deltamethrin were done on 20 November 2015 and on 10 February, 10 March and 24 May 2016, and fumigation of maize with phosphine was done on 10 February, 24 May and 25 June 2016. The lowest r.h. occurred between December and February, and then increased until the end of the monitoring period in July, and the coolest temperatures occurred in June and July, although temperatures were always above 25 °C (Fig. 3A).

P. interpunctella and *T. castaneum* were the most consistently captured species inside the warehouse, but captures of all species tended to be relatively low throughout the study (Fig. 3B). Overall the diversity of species and the average number captured tended to be greatest prior to January 2016, during the period when warehouse was empty prior to maize re-stocking. *R. dominica* was never

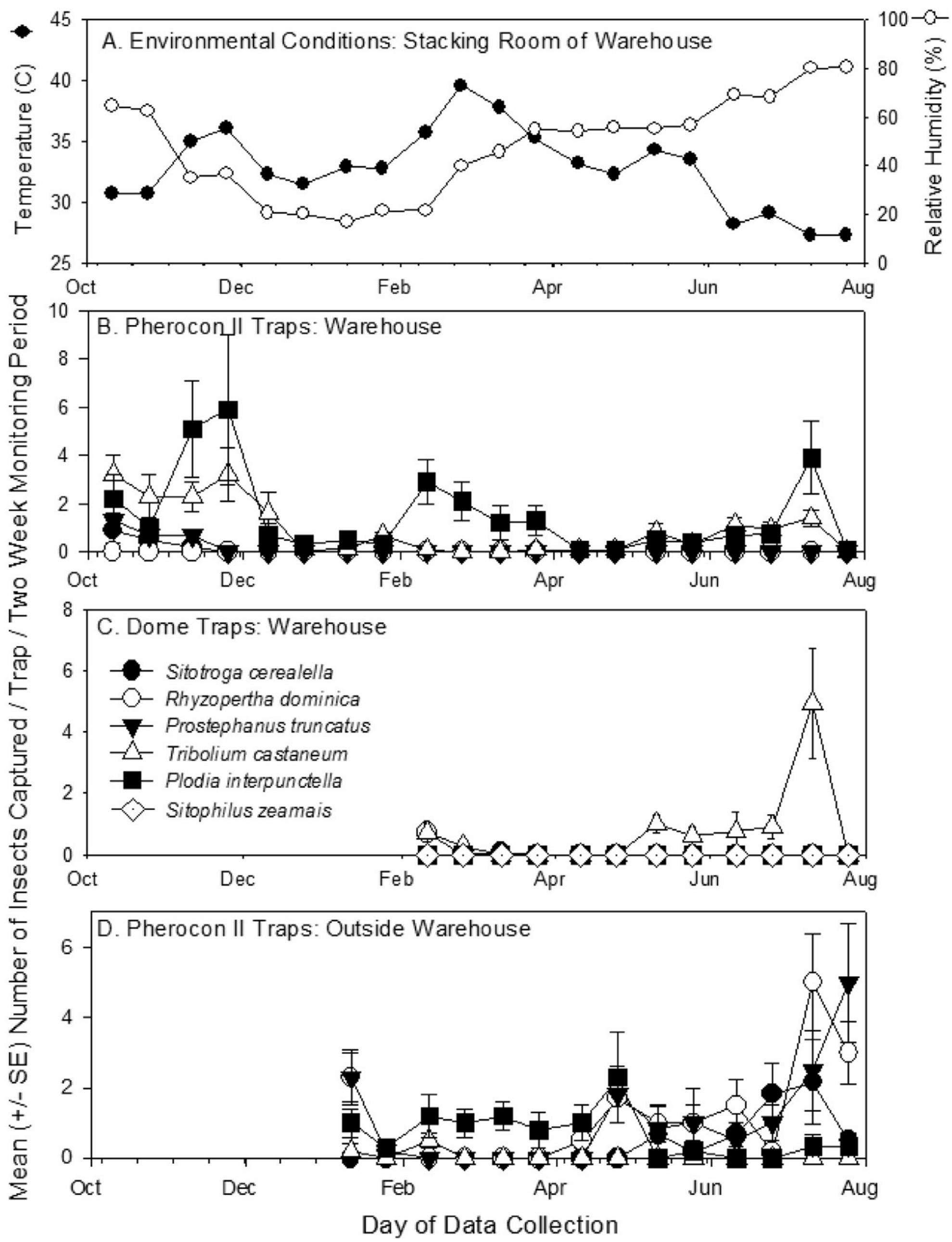

Fig. 3. Weinco warehouse, Northern Belt of Ghana, temperature and r.h. in stacking room of warehouse (A) and mean (±SE) number of insects captured/trap in the preceding two-week monitoring period in (B) Storgard II traps placed in warehouse (B), Dome traps placed in warehouse (C), and Storgard II traps placed outside the warehouse (D).

captured inside this warehouse, and *S. cerealella* and *P. truncatus* were only captured in the first three monitoring periods. In the Dome traps, only *T. castaneum* was captured, with the exception of four *R. dominica* that were captured on the first sampling period in February 2016 (Fig. 3C).

Outside the Wienco warehouse, all the insect species targeted for monitoring were captured, and generally were active throughout the monitoring period, except for February and March when only *P. interpunctella* was captured (Fig. 3D). *P. interpunctella* captures decreased from May through July, when captures of the other species tended to increase. *T. castaneum* was only captured during January and February. Interestingly, all three primary pests of whole maize, *P. truncatus, R. dominica* and *S. cerealella,* were active outside of this warehouse, especially in the period between May and July 2016, but inside captures were generally very low.

3.2. Farms near MiDA and Wienco warehouses

All species of insect pests targeted using specific pheromone lures were recovered in July at the farms near MiDA and Wienco warehouses (Fig. 4). Although not commonly captured at the warehouses, *R. dominica* and *P. truncatus* were the most predominant insect pests captured at both farm locations, with mean numbers captured ranging from 14.6 to 21.8 insects/trap and from 7.6 to 14.8 insects/trap, respectively. *S. cerealella, P. interpunctella* and *T. castaneum* were captured at the farms, but tended to be present in much lower relative numbers then at the warehouses. *Sitophilus* spp. were not captured at the farms, but the traps used

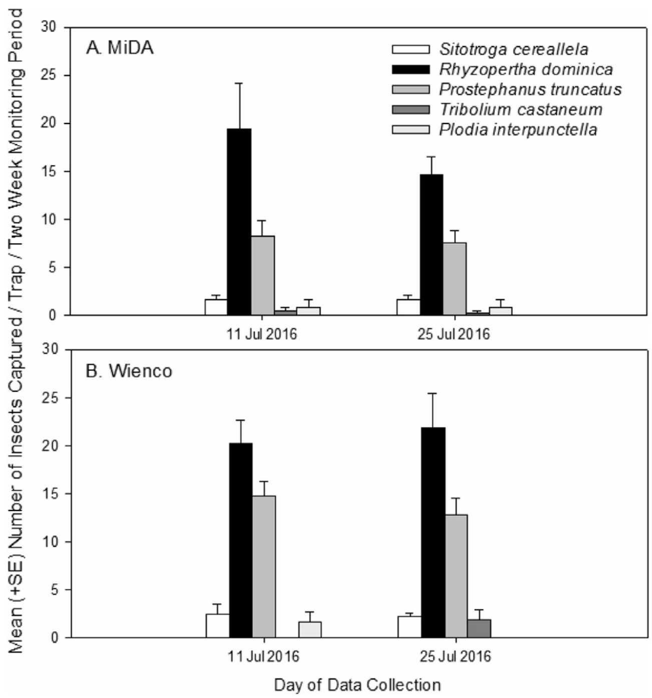

Fig. 4. Mean (+SE) number of insects captured in Storguard II traps per two-week monitoring period when traps placed on farms near the MiDA (A) and Wienco (B) warehouses in the Northern region.

would typically not capture weevils so this does not necessarily indicate that they are not present at farm locations.

4. Discussion

Results from this study show that many of the major stored product insect pests are associated with maize storage warehouses in both the Middle Belt and Northern Belt of Ghana. Capture levels and diversity tended to be higher outside the warehouses and at nearby farms, with less damaging secondary pests tending to dominate in trap captures inside warehouses. These findings show the utility of pheromone trapping to provide information on effective integrated pest management. Data also show that for reliable information on the insect numbers, it is prudent to use both Storgard II traps and Dome traps for monitoring flying and crawling insects simultaneously, especially since the important *Sitophilus* spp. pests cannot be monitored well with Storgard II or other flight-based traps. Our data show that *S. cerealella* and *P. truncatus* may be more important as pre-storage or on-farm storage insect pests, since they tended to be found more on the farm and outside of warehouses rather in the buildings. Danso et al. (2017) found that *Sitophilus* spp. and *S. cerealella* were abundant in maize samples collected at farm fields. Proper disinfestation of the maize and proper drying prior to storage in warehouses combined with the environmental conditions present in the warehouses during storage may create a less favorable environment for these species. *P. interpunctella* was the most dominant insect species and was most abundant in warehouses when bags of maize were present. It was also abundant outside of warehouses as well. Further research is needed on pest levels and the impact of different treatments in other warehouses to confirm our findings, but the warehouse with the most intensive pest management program had the fewest insects. Also, the relationships between captures in traps and pest levels inside the bags of maize and the relationship between inside pest activity and potential sources in the surrounding environment need further evaluation. Temperature and r.h. were not significantly correlated with captures of any of the insect species in Dome or Storgard II traps (data not shown, all Pearson Correlations were not significant except for a negative relationship between *R. dominica* captures in Dome traps and r.h. (-0.462, $P = .004$, $n = 36$)). Lack of relationship is probably due to temperature and r.h. being in favorable ranges for insect development throughout the study.

Sitophilus spp. are widely considered to be an important pest in Ghana and we captured more in the Middle Belt where the MiDA warehouse is located, than in the Northern region warehouses in Tamale. While we did not use a pheromone in the traps for *Sitophilus* species, the Dome trap with the food oil can be used to monitor for these species. However, it is likely that traps with pheromone lures may be more effective at attracting individuals and thus abundance of this species may be under-detected. *Sitophilus* spp. develop better in grain with higher moisture content and the trend for a higher average r.h. at the time that maize was initially introduced to the warehouse that we observed, would be associated with a higher equilibrium moisture content. Relative humidity increases in the Middle Belt of Ghana during the periods of February–August (Jarvis et al., 2014). Temperature may also play a factor in the prevalence of different species. For example, *S. zeamais* can outcompete *P. truncatus* at 25 °C, but the competitive outcomes are less certain at 30 °C (Giga and Canhao, 1993). Higher levels of primary feeders such as *Sitophilus* spp. may also contribute to higher levels of secondary pest activity, which might be related to greater activity later in the monitoring period.

Two of the more damaging primary pest species that are found in Ghana were not captured in high numbers in the warehouses. *S. cerealella* was captured in greatest numbers in the pre-storage stage in the receiving rooms of the warehouses and substantial numbers were collected in the farm and outside warehouse traps. In the subtropical and warm temperate regions of the world *S. cerealella* is major pest of grain both pre- and post-harvest hence the infestations might originate at the farm through infestation of maize in the field before harvest and while piled before shelling. The high temperatures reported in the warehouses during many parts of the year may also have not favored this species. The optimal temperatures for *S. cerealella* development and survival are 30–32 °C, with the lowest net reproductive rate at 35 °C (Grewal and Atwal, 1967; Hansen et al., 2004). *P. truncatus* is more damaging to maize on the cob and thus is likely to be more important in the field and when maize is stored on the cob, and is likely less important in warehouses storing shelled maize in bags (Cowley et al., 1980; Golob et al., 1985). In our study, very few *P. truncatus* were recorded inside the warehouses where shelled grains were stored, but its numbers were higher in the outside traps and especially in farm traps. Times when *S. cerealella* and *P. truncatus* were captured tended to be early in the study, when maize was being harvested and stored in the field prior to being bagged and stored in the warehouse. This pattern is consistent with these species being more significant field and farm pests. *R. dominica* was captured outside the warehouses, but was not commonly recovered in the warehouses, even though the ability of *R. dominica* to immigrate into warehouses in the United States has been previously reported (Toews et al., 2006). Our results suggest that if maize is properly cleaned and dried before being stored in warehouses, these species may be less significant pests than during storage at the farm level.

A significant factor for protecting stored products is having a good sanitation program as part of an Integrated Pest Management (IPM) program (Suss and Locatelli, 1993; Rotundo et al., 1995). Preventative sanitation creates a less favorable environment for pest insects and does not encourage establishment and spread.

P. interpunctella was the most dominant insect species inside the warehouses in both the Northern and Middle Belt regions. *T. castaneum* was also common in some of the warehouses. Presence of these insects may indicate problems with sanitation programs in a warehouse. However, given their mobility, ability to enter facilities, and wide host range, *P. interpunctella* activity within a facility may be influenced by the surrounding environment as well (Campbell and Arbogast, 2004). High levels of these species may also be associated with activity of primary feeders damaging the whole kernels. Generally, cleanliness in Gundaa and MiDA warehouses was poorer and sanitation was less timely than in the Wienco warehouse, which had more regular cleaning. The Wienco warehouse also had more frequent insecticide treatments. Comparing the average capture of *P. interpunctella* among the warehouses, Wienco had the lowest average moth capture at 1.5 ± 0.7 individuals per trap across the total monitoring period, while Gundaa averaged 7.9 ± 2.5 individuals per trap and MiDA averaged 14.4 ± 1.8 individuals per trap. There was a similar trend of *S. zeamais*, Wienco had no captures of this species, while Gundaa averaged 0.2 ± 0.2 individuals per trap and MiDA averaged 2.0 ± 0.9 individuals per trap. However, not all species followed this trend, with *T. castaneum* for example having similar low average captures across locations. These trends suggest a relationship but care needs to be taken in interpretation since location and other physical and management differences among warehouse may also impact insect activity. For example, the Wienco warehouse also had frequent fogging with deltamethrin insecticide, and while regular aerosol treatments may help suppress fluctuations in insect numbers (Campbell et al., 2010), they can also reduce insect movement and decrease capture in traps (Toews et al., 2005). In general, the Northern Belt warehouses had less insect activity, perhaps due to the dryer and warmer climate.

The use of insect trapping programs in and around a warehouse helps to document not only the presence or absence of an insect species, but also the seasonal patterns of abundance and the impact of pest management tactics. This information can be used to determine the risk of insect infestation that the stored commodity is under as well as helping to assess potential infestation levels of stored products in the warehouse. Data can also be used to help decision making by managers of facilities such as storage warehouses. With the increasing use of warehouses in Ghana and other areas of Africa for the storage of grain, it is important to get baseline data on levels of pest activity. Previous research has tended to focus on on-farm storage of maize, while the results reported here the first data collection regarding insect infestation levels in maize storage warehouses in Ghana. Our results suggest that the significance of different pest species may be different during warehouse storage compared to on-farm storage, which could impact monitoring and management programs. Overall results show that while there is variation in pest activity among warehouses, important pest species can be recovered inside and immediately outside storage facilities. This indicates that all the maize stored in these warehouses is vulnerable to infestation during warehouse storage.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jspr.2018.01.001.

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