Lessons learned for phosphine distribution and efficacy by using wireless phosphine sensors

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Extended abstract

1. Introduction

Phosphine is by far the most commonly used fumigant for disinfestation of stored grains, pulses etc. and also of dry processed commodities (Fields and White, 2002; Opit et al., 2012). For instance, approximately 80% of the grain production in Australia is fumigated with phosphine (Collins et al., 2001). It is a colorless, odorless and flammable toxic gas (Chaundhry, 2000). Phosphine is generally cheap, easy to apply for most durable commodities and it is effective for all life stages for nearly all the major insect pests, whereas it leaves minimal residues (Chaundry, 2000; Hasan and Reichmuth, 2004; Wang et al., 2006; Nayak and Collins, 2008). However, the extensive use of phosphine, in conjunction with low concentrations and poor sealing, has raised resistance issues and may lead to serious fumigation failures (Zeng, 1999; Collins, 2009). Currently, resistance by various storage insect populations is a reality in several parts of the world (Collins et al., 2002; Daglish, 2004). There are many traditional techniques available for monitoring gas concentration such as digital monitors that are placed outside of the treated area and glass tubes that are used to quantify concentration by sucking air from the treated substrate. Both methods are difficult in their use, often inaccurate and they need specialized personnel. Despite the fact that there are different types of electronic equipment that can be used to estimate phosphine concentration, the majority of them cannot be placed inside the treated area, due to the corrosiveness caused by this gas.

Recently, phosphine wireless sensors that can be placed inside the treated area have been developed and evaluated with success in storage facilities in Greece (Athanassiou et al., 2016). This initial work clearly indicated that gas concentration is uneven in the treated area, and that further experimental work is needed to evaluate its distribution. Moreover, it has been reported that inside a flour mill in the Czech Republic phosphine concentration varied remarkably, and the main factors for these variations were temperature and relative humidity gradients (Aulicky et al., 2015). Phosphine distribution in silos has been modelled by Isa et al., (2016) but there is still inadequate information regarding the effect of different biotic and abiotic factors towards this direction. At the same time, there are not many data available for the distribution patterns and spatio-temporal movement of phosphine in other commercial storage formations and facilities, such as containers, warehouses, silos and shipholds. Thus, the purpose of this study is to evaluate wireless phosphine sensors by estimating both gas concentration and kill rates of major stored product insects in "real world" tests.

2. Materials and Methods

2.1 Test insects

Adults of the lesser grain borer, *Rhyzopertha dominica* (F.) (Coleoptera: Bostrychidae) and the saw-toothed grain beetle, *Oryzaephilus surinamensis* (L.) (Coleoptera: Silvanidae), were used in the trials. The insects used were reared at the Laboratory of Entomology and Agricultural Zoology (LEAZ), Department of Agriculture, Crop Protection and Rural Environment, University of Thessaly, at 25°C, 65% relative humidity (r.h.) and continuous darkness. For each of the above species, two

populations were used in the experiment, one field and one laboratory population, namely GA6 *R. dominica*, ASC11 *O. surinamensis*, laboratory *R. dominica* and laboratory *O. surinamensis*. The laboratory populations are being reared for more than 20 years under laboratory conditions. The field populations were collected from different storage facilities from Greece and were characterized as tolerant to phosphine. From the above species, *R. dominica* was reared on whole wheat kernels, whereas *O. surinamensis* on oat flakes.

2.2 Experimental procedure

Plastic cylindrical vials (3 cm diameter and 8 cm in height) were the experimental units for the tests; the vial neck was covered with Fluon (polytetrafluoroethylene; Northern Products, Woonsocket, RI) to prevent insects from escaping. Each vial was filled with 10 g of commodity, i.e., whole wheat grain for *R. dominica* and oat flakes for *O. surinamensis*. Then, ten adults of each species and population were introduced into each vial (separate vials for each species and population). In each fumigation trial, the vials were placed in different locations within each facility. For each species and population three vials were prepared per location and per facility. Separate vials with insects, placed in untreated areas of each facility served as controls. Then the vials were transferred to LEAZ and adult mortality was assessed. The vials were kept in incubators set at 25ºC, 55% r.h. in continuous darkness and progeny numbers were recorded 65 d later. Phosphine concentration monitoring was performed by the use of wireless sensors (Centaur Analytics Inc. CA, USA), and wireless signal amplifiers and receivers were connected to computers. The sensors were placed at various locations inside the treated area, including all the locations where insects had been placed.

2.3 Data analysis

All data, separately for each trial and insect species were submitted to Independent t-test, with insect mortality as the response variable. To determine the effect of location for each trial, data were subjected to an one-way ANOVA with insect mortality as the response variable and location as the main effect. Control mortality was generally low, so the data for control mortality were not used in the analysis. The same approach was also followed in the case of progeny production counts. Means were separated by using the Student's *t* and Tukey-Kramer HSD test at 0.05, whenever this test was considered necessary.

3. Results

Figures below show the results according to the fumigation treatment at different facilities, i.e., a warehouse, a container, two shipholds and two silos, with wireless phosphine sensors which were located in the fumigated area (Figs. 1, 2, 3, 4, 5, 6). In all cases, the mortality of control was generally low for all insect species and populations and did not exceed 10%. Regarding the fumigation which was carried out in the warehouse, complete control was detected only for the *O. surinamensis* laboratory population in contrast with the other three populations tested (Tab. 1). In that facility, the maximum level of phosphine concentration was 80 ppm for less than four days (Fig. 1). On the other hand, in the fumigated container, mortality reached 100% for all tested populations, while the concentration of phosphine was 2000 ppm for five days (Fig. 2). Furthermore, at the fumigated shipholds, where no forced recirculation system (J-system) was applied, mortality was complete (100%) only for the laboratory population of *O. surinamensis*. Moreover, progeny production in the treated substrate was lower when the J-system was applied, but parental survival could not be avoided. In these treatments, the concentration of phosphine reached 300 ppm for two days (Fig. 4). Regarding the fumigation which was carried out in the silo, the concentration of phosphine ranged between 200 and 600 ppm (Fig. 5), which clearly indicated that phosphine could not be distributed normally in the treated grain mass. The use of J-system in a silo showed that the phosphine concentration gradually increased (Fig. 6).

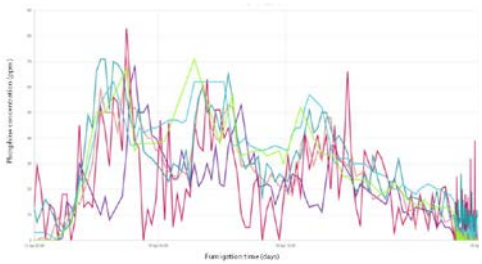

Fig. 1 Phosphine concentration during the fumigation inside a warehouse with six different wireless sensors (shown with different colors) placed at different locations.

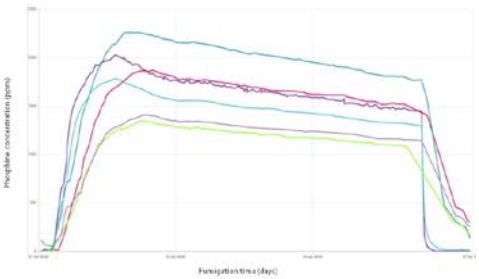

Fig. 2 Phosphine concentration during the fumigation inside a container with six different wireless sensors (shown with different colors) placed at different locations.

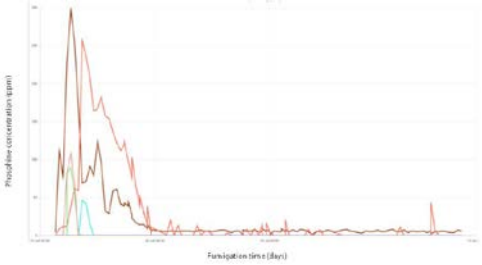

Fig. 3 Phosphine concentration during the fumigation inside a shiphold with five different wireless sensors (shown with different colors) placed at different locations.

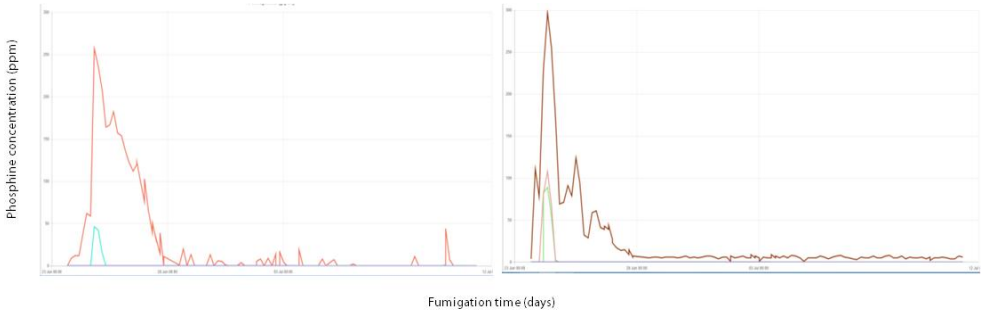

Fig. 4 Phosphine concentration during the fumigation in a ship hold with no use of recirculation system (left) with two different wireless sensors and in a ship hold with the use of a recirculation system (right) with three different wireless sensors (shown with different colors), placed at different locations.

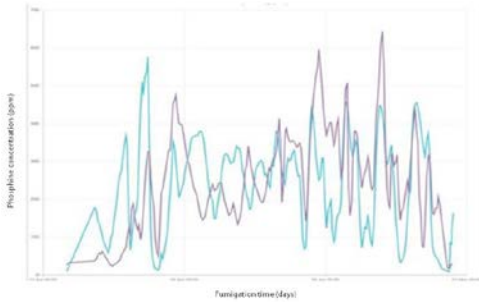

Fig. 5 Phosphine concentration during the fumigation inside a silo with two different wireless sensors (shown with different colors) placed at different locations without using forced recirculation system.

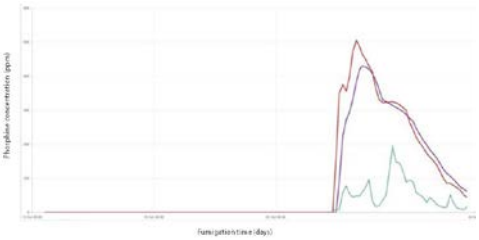

Fig. 6 Phosphine concentration during the fumigation inside a silo with three different wireless sensors (shown with different colors) placed at different locations by using forced recirculation system.

Tab. 1 Mortality (% ± SE) of parental adults for field and laboratory populations, in different facilities in which phosphine had been applied and the respective progeny production (number of adults per vial ± SE) 65 d later.

Facility	Insects	Mortality	Progeny production
Warehouse	ASC11 *O. surinamensis*	100 ± 0.0	0.0 ± 0.0
	Lab *O. surinamensis*	100 ± 0.0	0.0 ± 0.0
	GA6 *R. dominica*	100 ± 0.0	2.0 ± 0.7 a
	Lab *R. dominica*	100 ± 0.0	0.0 ± 0.0 b
Container	ASC11 *O. surinamensis*	34.2 ± 3.3 a	65.1 ± 11.4 a
	Lab *O. surinamensis*	100 ± 0.0 b	0.0 ± 0.0 b
	GA6 *R. dominica*	6.6 ± 2.2 a	48.4 ± 3.8 a
	Lab *R. dominica*	75.7 ± 4.1 b	12.6 ± 3.3 b
Shipholds	ASC11 *O. surinamensis*	not measured	0.3
	Lab *O. surinamensis*	not measured	0.0
	GA6 *R. dominica*	not measured	52.7 a
	Lab *R. dominica*	not measured	1.0 b

Within each trial and each species, means followed by different letters are significantly different. Where no letters exist, no significant differences are noted with Student's test at 0.05.

4. Discussion

In the fumigation treatments, we found high survival percentages of exposed adults and a considerable number of offspring in all cases, with the exception of the fumigations in the containers, in which complete control (100% mortality) was detected. This was partially due to the short duration of fumigation (approx. three to four days), in combination with low concentrations of phosphine in the warehouses, silos and shipholds. Phosphine leakage and sorption by the treated commodity are highly responsible for gas losses during fumigations (Bell, 2000, Aulicky et al., 2015). As a consequence, there was a sufficient number of insects that survived fumigation, and this number could gradually lead to resistance development. On the other hand, the fumigations in containers, which were the "best case scenario" here, clearly suggest that, if applied properly, phosphine can definitely lead to 100% efficacy levels. In the current trial, the container fumigation resulted in complete parental mortality, in conjunction with extremely low numbers of progeny production. In this context, for the same reasons noted above, fumigations in shipholds and silos are likely to fail due to increased leakage, which cannot be detected and quantified easily with the majority of phosphine detection techniques. In this regard, wireless phosphine sensors can be a valuable tool towards this direction (Athanassiou et al., 2016). Based on our results, in large areas, such as silos, distribution of phosphine was rather limited and thus, there were large areas within the grain mass that did not get enough gas in order to achieve a satisfactory insect mortality. The

adoption of a recirculation system in these cases can improve fumigation results. Summarizing, our tests clearly indicated that phosphine sensors were quite effective in measuring phosphine concentrations and can play an important role in the future in IPM-based programs during the post-harvest stages of agricultural commodities. Hence, sensors can be used as a "precision fumigation" tool and provide real-time estimates for insect control.

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Use of a 3D Finite Element Model for Post Fumigation Phosphine Movement Analysis

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Abstract

Phosphine is a dangerous gas commonly used in fumigations throughout the world. Grain that has not fully released the phosphine it absorbed during fumigation may continue to desorb phosphine into the headspace of a storage structure. U.S. OSHA standards for handling phosphine state the acceptable limit at 0.3 ppm. If this limit is exceeded grain handling may become dangerous. It is important to understand the process of phosphine