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Sensitivity analysis of a fumigant movement and loss model for bulk stored grain to predict effects of environmental conditions and operational variables on fumigation efficacy

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In order to improve fumigation effectiveness and address phosphine resistance concerns, fumigant concentrations and movement in a grain storage silo need to be understood. In a previous study a mathematically accurate fumigation model was developed that is capable of predicting fumigant concentration and movement throughout a grain storage silo by taking into account fumigant loss from leakage and sorption. This model was used to investigate the impact on a phosphine fumigation with changing operational variables and environmental conditions. These included modifying the initial values from the fumigation by ± 25% and 50% for leakage rates, air recirculation rates, air temperature, relative humidity, and wind speed. Reducing leakage rate to 50% and 75% of the original rate increased fumigant concentrations by 111% and 36% compared to −21% and −34% for 125% and 150% leakage rate changes, respectively. Likewise, by the end of the simulation, average phosphine concentrations changed by 118%, 41%, −28%, and −47% for the 50%, 75%, 125%, and 150% air recirculation rates, respectively. Results underline the importance of designing well sealed silos and the importance of monitoring fumigations during high wind speed weather events.

1. Introduction

Australian export regulations beginning in 1963 dictate an export limit of zero live insects. This regulation is highly impactful, as the Australian grain industry relies heavily on exports, with the quantity of exported grain reaching 90% of the harvest in Western Australia (Calderon and Barkai-Golan, 1999). As a consequence, fumigations have become the primary form of pest control. The primary fumigant used in stored grains and grain foods is phosphine (PH_3) because it kills all insect life stages at low cost and is easily applied in a variety of forms. However, overuse and misuse is leading to increased insect resistance to phosphine in many parts of the world, including most recently the United States (Opit et al., 2012). Insect resistance to phosphine is made worse when insect life stages are exposed to sub lethal doses of phosphine in a suboptimal fumigation. In order to extend the usefulness of phosphine as the primary stored grain and grain food fumigant, and reduce the risk of spreading resistance development among stored product insects, phosphine fumigation efficacy must be improved.

An effective fumigation requires a specific concentration of fumigant being held for a specified amount of time in all areas of the silo, in order to kill all life stages of all insects present. Computer modeling is a useful tool to analyze the combined effect of the parameters that influence fumigant concentrations in a grain storage silo, and as a function of geographic locations and climatic conditions (Casada and Noyes, 2000). In 'On criteria for success of phosphine fumigations based on observation of gas distribution patterns' Banks and Annis (1984a,b) list a number of criteria to determine the success of a commercial fumigation including (1) the average maximum concentration of phosphine must be more than 50% of the theoretical amount of phosphine applied, (2) the concentration at the end of the exposure period must be greater than the minimum effective against insects, and (3) the ratio of minimum to maximum concentration must exceed 0.25 after not more than 25% of the exposure period.

Fumigant concentrations can be influenced by several factors

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including ecosystem conditions such as moisture content of the grain mass (Reed and Pan, 2000), temperature of the grain mass (Banks and Annis, 1984a,b; Darby, 2011; Reed and Pan, 2000), temperature differences between the grain mass and ambient air (Banks and Annis, 1984a,b), and wind speed (Banks and Annis, 1984a,b; Cryer, 2008). Wind and temperature based effects are considered leak dependent major forces in fumigant loss (Navarro, 1998). In addition, a fumigation is also influenced by a number of engineering variables such as fumigant recirculation rate, amount of phosphine applied, rate of evolution of phosphine into gaseous form, and leakage rate of the silo. Fumigations that recirculate gas have several advantages over passive fumigations, including reduced grain handling shrinkage, lower necessary dosages, faster fumigations, less required labor, improved worker safety, less phosphine in the environmental phosphine, reduced insect resistance, and reduced overall cost of fumigation (Noyes et al., 1998). However, in addition to fan-forced recirculation, passive recirculation methods are also being used. In these systems, air recirculation is produced by the effect of temperature and solar radiation on an external piping system, called a thermosiphon. The comparative effects of thermosiphon recirculation have not been well studied.

A better understanding of how environmental factors and operational procedures influence a fumigation would allow applicators to take more effective corrective actions to prevent fumigation failures. There are a number of factors that may deter the efficacy of a fumigation where enough fumigant was applied to theoretically control the insects. According to Banks and Annis (1984a,b) these factors are excessive overall loss of fumigant, inadequate fumigant dosage in localized regions, excessive delay between application and fumigant reaching particular regions, or a combination of these factors occurring simultaneously. To observe whether any of these effects were occurring in a fumigation would be difficult and would require excessive monitoring of fumigant concentrations at a number of locations in the silo. Even with such controls, there could be regions that are not monitored and experience problems, or environmental conditions that are abnormal or unforeseen. For these reasons, simulation with a three-dimensional ecosystem model that can predict phosphine values at key locations in the silo can be of use.

The objective of this research was to use a mathematical model developed and validated by Plumier et al. (2018) to investigate the effects of environmental conditions (i.e., temperature, relative humidity, and wind speed) and operational variables (i.e., recirculation rate, leakage rate, and silo dimensions) on fumigation efficacy.

2. Materials and methods

In order to quantify effects of environmental conditions on predicted fumigant movement and loss, the Maier-Lawrence-Plumier (M-L-P) 3D ecosystem model that has been verified in its ability to analyze phosphine fumigations was used (Plumier et al., 2018). The same mesh from Plumier et al. (2018) was used, with 2587 nodes was created in the Abaqus finite element software for the simulation based on the dimensions of the silo supplied. The silo used is a Bird's model 2250 from Bird's Silos and Shelters in Popanyinning, Western Australia, with a 4.4 m diameter, 6.93 m peak height, capable of storing 45.5 tonnes of maize. The silo was equipped with a thermosiphon gas recirculation system that consists of an external pipe designed to induce air currents as a result of temperature and solar radiation. The cylindrical portion of the grain mass that was used in the simulation was 4.4 m in diameter and 3.96 m high. The reported pressure half loss time was 31 s, as recorded the morning of the trial start. The targeted concentration-time (Ct) product for this fumigation was 21,600 ppm-h.

In the previous paper on this research, new equations were developed to predict phosphine loss from sorption and leakage from the fumigation in question from factors such as the effects of weather, but were not extended to analyze changes in the system generally. The original 10-day fumigation was conducted from Aug 31 to Sept 9, 2015 in Manhattan, Kansas. Weather data for that time period was acquired from the Kansas State University Mesonet database (http://mesonet.k-state.edu/). This weather data was modified by changing hourly values of each key parameter (wind speed, ambient temperature, relative humidity) by ± 25% and ± 50%. The effects of fumigant recirculation and silo leakage were analyzed with changes of ± 25% and ± 50%. Average, standard deviation, maximum, and minimum weather conditions are shown in Table 1. The 50% increase in temperature resulted in an average temperature of 41.4 °C, just shy of the record high for Aug 31 of 42 °C. The 50% reduced temperature was an average of 13.8 °C, while the record low for Aug 31 was 5 °C. The modified simulations were compared to a base case that used the original weather data to simulate the fumigation in Cook (2016).

3. Results and discussion

3.1. Effect of operational variables

3.1.1. Effect of changing leakage rate

A successful fumigation requires a well-sealed silo. Among other factors, the amount of leakage from a silo depends on the leakage rate that makes a fumigation either successful or a failure. Recommended values for pressure half loss time vary by size of silo and range from 3 min for a 500 m^3 silo to 6 min for a 2000 to 15,000 m^3 silo (Navarro, 1998). An approximate rule of thumb for silo fumigations in Australia is pressure half loss times of 3 min or greater tend to assure a successful fumigation, while two to 3 min might cause failure or success, and less than 1 min would cause a failed fumigation (Manoj Nayak, Personal Communication).

Shown in Fig. 1 are the predicted average phosphine concentrations for five simulations with a varying leakage rate, expressed as percentages of the leakage rate from the model verification (i.e., 100%). As expected, phosphine concentrations were higher for silos with a lower leakage rate. The effect is not directly proportional, as halving the leakage does not result in halving of the concentrations in the silo. Instead, halving the leakage resulted in a phosphine concentration that when averaged over all locations and times was 30% greater than the concentration from the verification. At 1.5x the leakage rate, the same overall average phosphine concentration was 12% less than the overall average concentration from the verification. Fumigations with lower leakage rates achieved higher maximum phosphine concentrations (416, 407, 400, 393, and 388 for 50–150%, respectively), as leakage begins taking effect before the maximum values are reached. The trends of decrease are similar throughout, despite the changes to leakage rate.

Percentage changes resulting from the five simulations are shown in Fig. 2. By the end of the simulation the percentage differences from original were 111%, 36%, −21%, and −34% for the 50%,

Table 1
Weather data for Manhattan KS from Aug 31 to Sept as acquired from the Kansas State University Mesonet database (http://mesonet.k-state.edu/) and used as baseline for this study.

	Temperature °C	Relative Humidity %	Wind Speed m/s
Average	27.6	61.7	2.7
Standard Deviation	4.1	15.9	1.3
Maximum	36.7	95.3	5.4
Minimum	18.2	33.5	0.2