Journal of
Stored Products and Postharvest Research

Volume 8 Number 2 February 2017

ISSN 2141-6567

Academic Journals

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Journal of Stored Products and Postharvest Research

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academicJournals

Vol. 8(2), pp.11-15, February 2017
DOI: 10.5897/JSPPR2016.0224
Article Number: 08E03D062557
ISSN 2141-6567

http://www.academicjournals.org/JSPPR

Journal of Stored Products and Postharvest Research

Full Length Research Paper

Assessment of sesame *Sesamum indicum* grain storage loss due to Indian Meal Moth *Plodia interpunctella* (Lepidoptera) for small scale-farmers in western zone of Tigray, North Ethiopia

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Received 26 September, 2016; Accepted 12 January, 2017

Sesame (*Sesamum indicum* L.) is one of the world's oldest oil seed crop grown mainly for its seeds. Insect pests are one of the most important factors affecting production and storage of sesame grain affecting both its quality and quantity. In order to assess and determine storage grain loss due to *Plodia interpunctella,* an assessment was conducted in western zone of Tigray (13°45' to 14°28' N latitude and 36°20' to 37°31' E longitude) in 2016. Sample of 1 kg sesame grain was taken from 10 small scale's storage houses in each districts. Collected data analyzed statically with one-way ANOVA. All locations were significantly similar on all parameters. An average weight loss of 17.8% and total percentage loss of 25.2% due to *P. interpunctella have been* recorded in the surveying areas. *P. interpunctella* has distributed throughout the sesame producing area of western zone of Tigray and found to be causing substantial grain loss, especially for sesame stored more than a year. Further studies *have to be conducted* on control strategies of Indian meal moth *P. interpunctella.*

Key words: Assessment, storage loss, *Plodia interpunctella, Sesamum indicum,* Western Tigray.

INTRODUCTION

Sesame (*Sesamum indicum* L.) is an annual crop from the Pedaliaceae family grown mainly for its seeds that contain approximately 52 to 57% oil and 25% protein (Weiss, 2000; Wijnands et al., 2007). Sesame annual worldwide grain production is around 4 million tonnes (FAOSTAT, 2014). In Ethiopia, the North West region is the major sesame seed production area (Alemu and Meijerink, 2010, Wijnands et al., 2007).

Sesame is a high value food crop, which is an important source of edible oil. The seeds are very rich in iron, magnesium, copper, calcium and vitamin B1 (thiamine) and E (tocopherol). The seed also contain phytosterols associated with reduced levels of blood cholesterol (Zerihun, 2012). Despite its importance, biotic and abiotic factors greatly affect production, productivity and storage of sesame. Insect pests are one of the most

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important factors affecting production and storage of sesame seed both in quality and in quantity. Several pests attack sesame, with potential to cause economic loss around the world. In Ethiopia however, only the sesame webworm (*Antigastra catalaunalis*) and gal midge (*Asphondilia sesami*) in pre harvest, sesame seed bug (*Elasmolomus sordidus*) in post-harvest (Geremew et al., 2012, Muez et al., 2008, Selemun, 2011, Zenawi et al., 2016a, b) and Indian meal moth (*Plodia interpunctella*) in grain storage are the major pests of sesame. In developing countries, damage caused by storage pests is 10 to 40% where in some rural areas is as high as 80% (Saeidi and Hassanpour, 2014).

In Ethiopia post-harvest losses, including storage losses was estimated at 5 to 26% (Dubale, 2014). The occurrence of post-harvest insect-pests, including *Sitophilus* spp., *Tribolium* spp. and *P. interpunctella* (Hübner) (Lepidoptera: Pyralidae) are main problems in sesame grain management (Géssica et al., 2015). The larvae of *P. interpunctella* is an external feeder which cause economic grain damages by feeding and secreting silky webs which permeate all substrate and contains larval frass (Filip and Snežana, 2012, Mohandassa et al., 2007). This moth species has very strong economic impact, because it uses a wide range of products in its diet (Filip and Snežana, 2012; Manuel, 2009).

Any research related to P. interpunctella has not conducted yet in the study area and assessing and determining grain storage loss due to the major storage insect *P. interpunctella* was an objective of the current study.

MATERIALS AND METHODS

Description of the study area

The assessment was conducted in low lands of western zone of Tigray (*Setit Humera, Kafta Humera* and *Tsegede*) (Figure 1|) located at 13°45’ to 14°28’ N latitude and 36°20’ to 37°31’ E longitude. It is 1000 km far from Addis Ababa via the Gonder road and bordered by Eritrea and the Sudan Republic in the north and west, respectively. The area has a flat topography with an altitude range between 500 and 800 m above sea level (m a.s.l). Based on the data from Humera Agricultural Research center (HuARC) metrological station, the area is characterized by arid climatic condition with mean temperature of 30°C and annual mean rainfall of 581.2 mm, which ranges from 380 to 870 mm.

Loss assessment

In western zone of Tigray, three districts (*Setit Humera, Kafta Humera* and *Tsgede*) were selected knowingly and 10 storages as well using the stratified sampling procedures in each district. Generally, 30 small-scale storages were sampled from the zone. One kilogram of sample was reserved randomly from the small-scale farmers’ sesame storage in each locality. At the time of grain sampling, moisture content of the grains was 7.2 to 7.8% when tested using a moisture meter.

Grain weight loss

Sesame grains are very fine; it is difficult to count manually therefore seed counter machine was used to count 1000 seeds of sesame from a sample. Web tied grains (cocooned) was removed or disbanding before counting. Then a device called illuminated purity work board was used to separate and count affected and unaffected grains. Healthy and damaged grains were counted also using the INDOSAN seed counter machine. Finally, both healthy and damaged grains had weighed using sensitive balance. To estimate the loss (percentage), each sample divided into damaged and undamaged grains and the percent loss had calculated using the following formula:

$$\textbf{Weight Loss (\%)} = \frac{(U*Nd)-(D*Nu)}{U(Nd+Nu)} \qquad (1)$$

Where Nu = No. of undamaged grains; Nd = No. of damaged grains; U = weight of undamaged grains; D = weight of damaged grains.

Number of cocoons, weight of cocoon and seeds per cocoon

The larva of *P. interpunctella* collects grains and webbing the grains together. Then after it pupate inside the webbed grains. Webbed grains has considered as it lost, because sacks with as such signs/symptoms are not acceptable for sale unless the webbed grains or cocoons removed by winnowing. Hence, number of cocoons or webbed grains per sample (1 kg) had counted and weighed. Grains in a cocoon had also counted and weighed by disbanding the webbed grains.

Percentage losses

The percentage losses sesame grains due to the pest feeding has calculated by taking 1000 grains randomly from the sample. The following equation has used to estimate the percentage loss:

$$\text{Losses due to feeding (\%)} = \frac{\text{Number of damaged grains}}{\text{Total number of grains}} * 100 \qquad (2)$$

The percentage losses due to webbing has also calculated by disbanding and weighing the grains in the cocoon/ webbed grains. The following equation has used to estimate the losses due to webbing:

$$\text{Losses due to webbing (\%)} = \frac{\text{Weight of webbed grains}}{\text{Sample weight(1kg)}} * 100 \qquad (3)$$

$$\text{Total Loss} = \text{Losses due to feeding} + \text{Losses due to webbing} \qquad (4)$$

To avoid the repetition during loss estimation of due to webbing and feeding, only damaged grains were used to estimate feeding loss whereas undamaged but webbed grains used to estimate webbing loss. Ethiopian Commodity Exchange (quality determining organization) rejects sacks that have webbed grains then collectors or producers enforced to winnow or screen it again in order to remove the webbed grains.

Statistical analysis

One-way-ANOVA by Gen Stat 14 was used for statistical evaluation and LSD (0.05) for means comparisons.

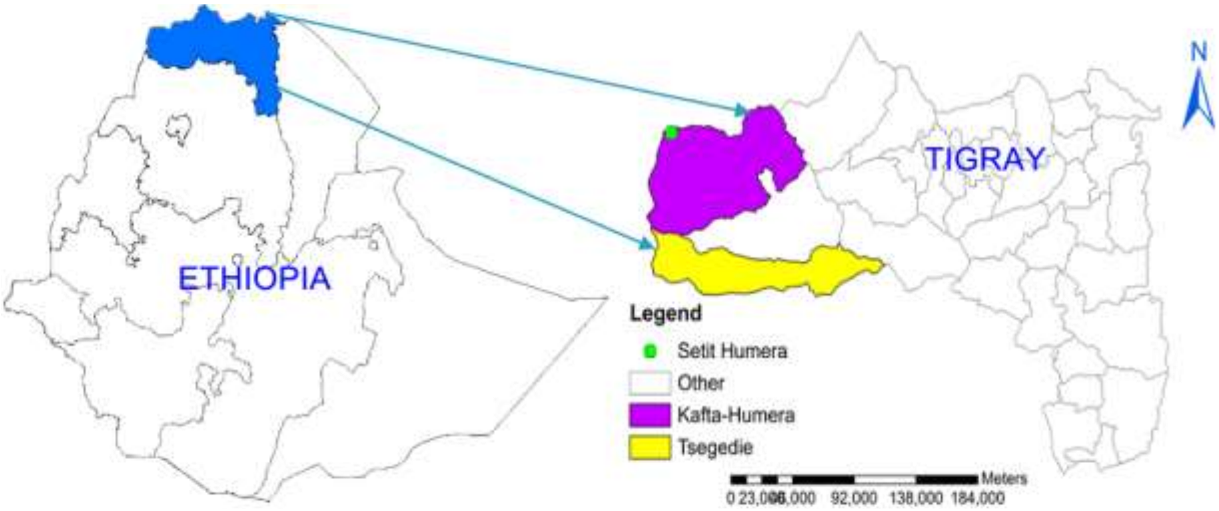

Figure 1. Map of the study locations.

Table 1. Means of grain weight loss, percentage loss, no. of cocoon/kg and seeds per cocoon of the different districts in western zone of Tigray.

Locations	WL%	FL%	WBL%	TL%	NC	NGC
Kafta Humera	16.4±7.5	19.7±9.1	4.0±2.3	23.8±10.3	30.6±8.3	155.3±55.2
Setit Humera	18.8±5.1	22.6±6.1	4.1±1.4	26.7±6.3	31.4±7.8	154.1±59.1
Tsegede	18.1±3.6	21.8±4.4	3.4±1.5	25.2 ±4.1	28.8±8.0	167.2±33.2
Grand mean	17.8±5.5	21.4±6.7	3.8±1.7	25.2±7.2	30.3±7.8	158.9±49.4
LSD (0.05)	5.562	6.694	1.561	7.482	6.82	47.98
CV%	33.3	33.3	43.4	31.6	24.0	32.1

WL= Grain weight loss; FL= percentage loss of grain due to insect feeding; WBL= percentage loss of due to grain webbing; TL= total loss (WBL + FL); NC = number of cocoons per kilogram of grains; NGC = number of grains per cocoon.

RESULTS

Grain weight loss

The pest has occurred (100%) in all assessed areas of western zone of Tigray (*Setit Humera, Kafta Humera* and *Tsegede*). Weight loss due to *P. interpunctella* in western zone of Tigray, is presented in (Table 1). Percentage of grain weight loss is not statically different across locations. However, an average weight loss due to the pest in the region for small-scale farmers was 17.8±5.5%.

Number of cocoons and grains per cocoon

Number of cocoons per a kilogram and number of grains per webbed grains has no significant difference (p=0.05) across locations. Within the zone, there was an average of 30.3±7.8 and 158.9±49.4 Number of cocoons per kilogram and number of grains per webbed grains, respectively (Table 1). The pest had almost similar number of cocoons per kilogram and number of grains per webbed grains in all assessed locations of the region.

Percentage loss

The result revealed that there was no significant difference across locations on percentage loss due to *P. interpunctella,* but a total percentage loss of 25.2%±7.2 has been recorded in the study areas (Table 1). When a percentage loss against storage period was inspected, higher grain percentage loss was recoded as storage period increased (Figure 2).

DISCUSSION

P. interpunctella has very strong economic impact, because it uses a wide range of products in its diet (Filip and Snežana, 2012). This pest is an external feeder almost eats the whole grain leaving the seed coat in one

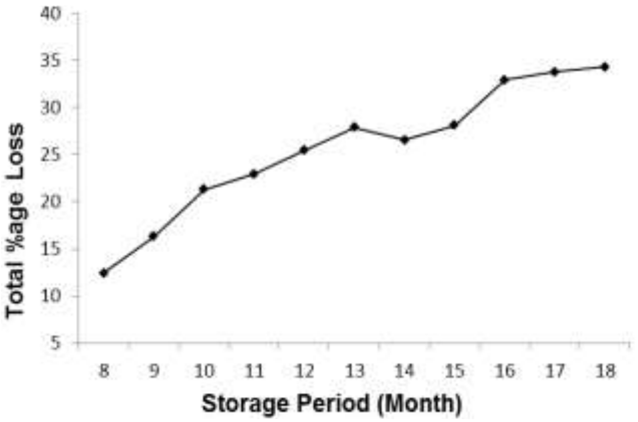

Figure 2. Sesame grain percentage losses due to *P. interpunctella* across storage periods.

Figure 3. Damaged (A); damaged and webbed (B, C &D) sesame grains by *P. interpunctella.*

side. Sesame grain yield/productivity in the study area is about 400 kg/ha (SBN, 2014). Of this 400 kg, about 71.1 kg is lost during storage due to *P. interpunctella* (when grain is stored for more than 12 months). May be the weather condition of the storage is suitable for the pest and since no control measures are available in the region, it could have similar distribution throughout all locations. Because the pest is new for the region and there are no mechanisms of control except farmers that winnow again to remove the cocoons/webbed grains (Figure 3). Moreover, this exposes the producers to additional costs and losses. A study conducted in western zone of Tigray, on *E. sordidus* found large weight loss (94.7%) of sesame grain (Muez et al., 2008). Dennis

(2001) reported that *P. interpunctella* has great role on grain weight loss of stored products. Similarly weight loss on oat by *Sitotroga cerealella* (same family with *P. interpunctella*) was found to be 25.7 up to 69.2% (Shahzaib et al., 2012).

Damage also occurs through the contamination of foodstuff with dead larvae, frass and silk webbing and causing heating and molding of the grain in addition to feeding (Géssica et al., 2015, Manuel, 2009). A study by Shahzaib et al. (2012) revealed that grain loss of 46.9% by storage moths (*S. cerealella*). *P. interpunctella* is the most common moth in stored food facilities and is the cause of most complaints from the food industry, sellers and consumers (Manuel, 2009).

Conclusion

P. interpunctella is economically very important pest in western Tigray, north Ethiopia, which causes about 18% weight loss in sesame grains. It is causing grain loss not only through feeding but also by creating silk and webbing the grains together. The pest has distributed throughout the sesame producing and/or storage area of the zone and it is causing substantial storage grain loss up to 25.2%. Based on the results of the assessment, it is better to conduct a designed study on control strategies of Indian meal moth *P. interpunctella.*

Conflicts of Interests

The authors have not declared any conflict of interests.

ACKNOWLEDGMENT

Even though this research did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors but the author would like to acknowledge Humera Agricultural Research center.

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Vol. 8(2), pp.16-30, February 2017
DOI: 10.5897/JSPPR2016.0227
Article Number: 305719B62559
ISSN 2141-6567
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Journal of Stored Products and Postharvest Research

Full Length Research Paper

Managing evolving insecticide resistance in stored grain pests within Avon Region, Western Australia

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Received 26 October, 2016; Accepted 3 January, 2017

The requirement that all Australian grain exports are insect-free relies on phosphine fumigation to control stored grain pests such as the lesser grain borer (*Rhyzopertha dominica*).The value of the current infrastructure in the grain storage, transport and handling network depends on the efficacy of phosphine fumigation. However, the biosecurity of the grain supply network is threatened by the emergence of Strong-Form Resistance (SFR) to phosphine in stored grain pests. SFR spreads from farm to farm through dispersion and by transport with grain through the supply network. The presence of SFR increases costs in the supply network as the number of fumigations per grain batch increases and the requirement to hold grain in sealed storage to achieve effective pest control increases. SFR in the short run increases costs of phosphine fumigation. In the long term it requires additional investment in sealed storage. This paper analyses the additional costs of SFR in the Western Australian Avon Region using three linked economic and bioeconomic models. Model 1 (farm to receival site) maximizes farmer's profit of delivering wheat from farms to receival sites. Model 2 (recieval site to port) minimizes the Co-operative Bulk Handler's (CBH) costs of transport, handling, storage and fumigation costs from receival sites to port. Model 3 (biosecurity – resistance spread) calculates the expected extra biosecurity cost of emerging SFR for the Avon wheat network. Our results show an increase in costs of between $8.8/t to $31.4/t of wheat depending on the rate of spread and the time horizon considered.

Key words: Phosphine fumigation, biosecurity, crop storage, wheat, stored-wheat outbreak, jump diffusion.

INTRODUCTION

Australia's $5 billion (DFAT, 2012) of grain export depends on the capacity of grain supply network to deliver grain free of stored grain pests to export grain terminals. A pest-free and insecticide free status adds value to the crop by allowing access to high price export markets. Since its introduction in the 1930s, phosphine fumigation has been relied upon to ensure that grain is pest free. Phosphine is cheap, residue-free, environmentally benign, and is effective against a wide range of insects in all grain crops (Chaudhry, 1997). Currently, about 80 % of grain stored in Australia is fumigated with phosphine (CSIRO, 2011). Therefore, the value to the grain industry of the continued use of Phosphine is substantial. For instance, at current costs of phosphine treatment relative

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to a methyl bromide or nitrogen alternative, the cost saving is about $15 million per annum in Australia.[1]

Phosphine resistance was first reported in Bangladesh (Tyler et al., 1983), and later in India (Rajendran and Narasimhan, 1994). The exact mechanism of resistance in grain insects to phosphine remains unclear (Price, 1984; Nakakita and Kuroda 1986; Chaudhry and Price, 1989, 1990; Chaudhry, 1997). There are two types of resistance in stored grain pests: weak form and strong form resistance (SFR). For instance, resistance in the Lesser Grain Borer (*Rhyzopertha dominica)*, the most ubiquitous and damaging grain pest, is controlled by two major genes that must both be present for SFR to be expressed. Weak resistance is expressed when only one of the genes is present (Collins, 2009).

In Australia, weak form resistance was first detected in New South Wales in lesser grain borer in 1990 (White and Lambkin, 1990) and SFR appeared in the same species in 1997 (Collins, 1998; Collins et al., 2002). In 2011, SFR in *Tribolium castaneum* was detected on two farms in the Western Australian (WA) wheat belt (Chami et al., 2011) and the outbreaks were eradicated[2].

Danger to the industry can stem from grain delivery to the cooperative bulk handling system of phosphine resistant strains of grain pests which may develop in farm storages through the use of phosphine in unsealed and poorly maintained sealed storages. (Emery et al., 2011). The spread can follow a number of paths. First, farm to farm spread and second, farm to receival site spread. A number of studies have observed the spatially and temporally patchy distributions of stored-product pests inside structures (Arbogast et al., 1998; Arbogast et al., 2000; Campbell et al., 2002; Nansen et al., 2004), and around the outside of storage structures (Campbell and Mullen, 2004). Stored-grain pests are often found 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), with refuges in non-agricultural locations, sometimes at a distance from grain stores (Cogburn and Vick, 1981; Sinclair and Haddrell, 1985; Strong, 1970; Vick et al., 1987), which suggests the capability of these insects for long distance movement and flight.

Laboratory studies with *R. dominica* -for example- showed that flight initiation and dispersal of newly emerged beetles were stimulated by external and internal factors such as age, population density, starvation, food quality and nutritional level, temperature, and time of the day (Mahroof et al., 2010).

Ching'oma (2006) studied the spatial distribution of *R. dominica* in an agricultural mosaic of wheat and sorghum fields in central Kansas, US, during 2003 to 2004. Trap captures tended to increase at times in the year when beetles were active across the whole landscape. In the same study, Ching'oma found the average dispersal distance of recaptured beetles to be 380.4 ± 10.5 m a year (Ching'oma, 2006). In addition to farm to farm spread, insects can also be dispersed over long distances through grain transportation and storage.

This form of local and long range dispersion is characterised by a jump-diffusion process (Kot and Schaffer, 1986). Biological invasions of pest, such as grain pests, are driven by a stratified dispersal process, where the initial range expansion is through local diffusion. Then, as the range of the local population expands, new colonies created by long distance migrants increase in number to cause an accelerating range expansion. The spread of the pest through time depends on how and where short and long distance dispersers are produced and the rate of dispersion.

Strong Form Resistance (SFR) poses a threat to current methods of grain storage and could reduce the value of storage infrastructure that is designed to manage pests by phosphine fumigation. This is the case for the large number of unsealed stores found in Avon Region in Western Australia.

The objective of this paper is to calculate the extra cost incurred by the onset of strong phosphine resistance SFR across a wheat transport and storage network, the Western Australian Avon region, over a 20-year planning horizon. This paper is, to our knowledge, one of the first to consider an integrated transport, storage and biosecurity management system. Increasingly supply chains have to consider the management, not only of the physical transport of goods, but also the management of pests. This approach has been applied to area wide pests such as fruit fly (for instance, Florec et al., 2012), but not to pest management within a supply network where the pest habitat is provided by storage infrastructure and the way it is managed.

Study area - Avon region, Western Australia

Kwinana port is WA's primary grain export facility. It can store up to a million tonnes of grain; about a fifth of production in the Avon region (5 million tonnes of wheat in 2008-09) (CBH data, 2009). The Avon agricultural region has about 6700 commercial farmers delivering by road to 110 country receival sites. In turn, the grain is delivered by rail (76%) and road (24%) from recieval sites to port. Figure 1 gives a map of the Avon region showing wheat shires (38 shires), wheat receival sites, and rail lines. Nodes of the wheat supply network consist of farms and receival sites, connected by rail and road. When grain is delivered to receival sites/port, it is sampled, weighed and fumigated and stored for some time at some fees (CBH, 2014). Thus, movement of wheat through the

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[1] Assumes four treatments for each tonne of grain, cost of phosphine is $0.12 per tonne and cost of alternative is $0.30per tonne. Wheat and coarse grain exports 25.4 million tonnes in 2012-13 (Schulte, 2013). This estimate is an underestimate of the costs as it does not account for the quality loss due to using a fumigant such as methyl bromide (UNEP, 2010).

[2] To our knowledge, this is the first time that a resistant stored grain pest has been demonstrated to have been eradicated.

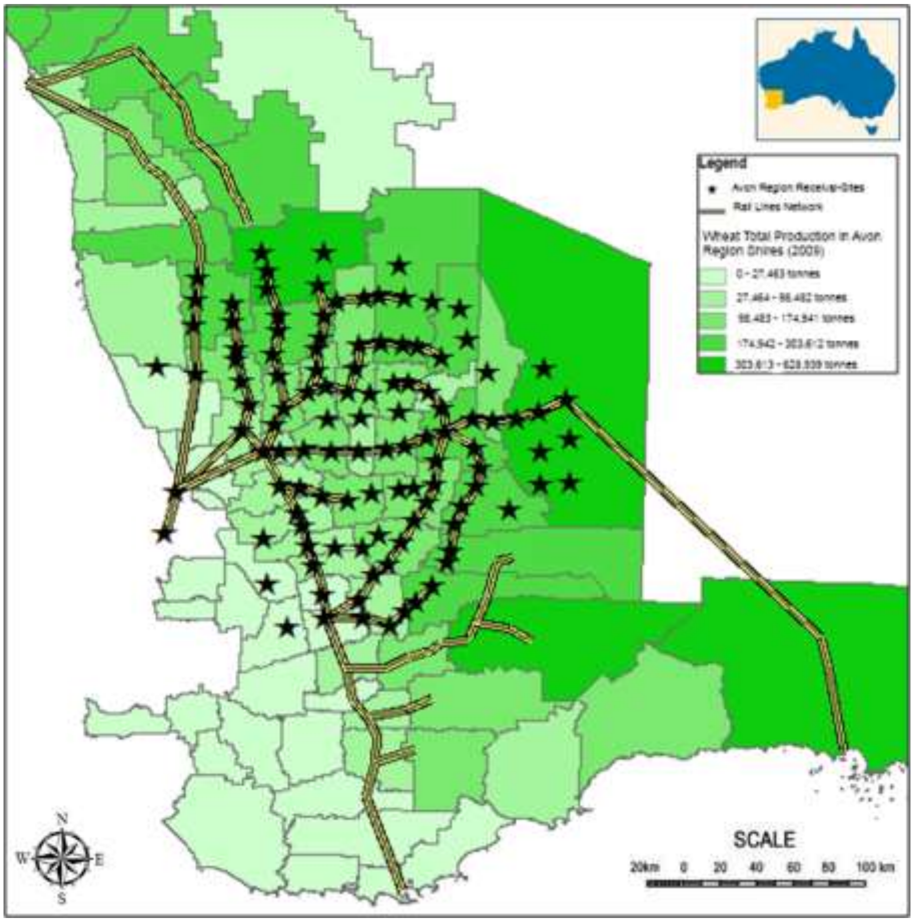

Figure 1. Wheat storage and transport network in Avon Region, WA.
Source: Authors' calculations and drawings; using ArcGIS Software.

network incurs costs of transport, handling, storage and fumigation against stored grain pests.

MODELS

Stored grain pests depend on the storage quality provided by grain stores. Two activities are included in the model: the allocation of grain from farms to receival sites (Model 1; farm to receival sites) and the movement of grain from receival sites to port (Model 2; recieval sites to port). Stored grain pests thrive in the grain supply network (in transit) as it provides them with a virtually unlimited food. An effective fumigation requires that the phosphine gas be held in the infested structure long enough to kill the target pests. So, regular exposure to poor fumigation processes may cause stored grain pests to develop resistance (Alabama Cooperative Extension System, 2005) (Model 3; biosecurity model). Thus; grain in storage (under favorable weather conditions) is conducive to insect growth, and the amount of grain in storage is influenced by economic decisions that determine how much grain is allocated by farms to receival sites, how much grain is sent from receival sites to ports and how much grain is stored at farms or receival sites.

Three models are described in this paper; the first two are complementary mathematical programming models. Model 1 (farm to receival site) maximizes the farmers' profit of delivering wheat to receival sites over three periods of time, and predicts the allocation of wheat from farms to receival sites. Model 2 (receival site to port) determines the minimum cost to the Co-operative Bulk Handler (CBH) of wheat transport, storage, handling and fumigation through the transport network between receival sites and Kwinana port. Model 3 (the biosecurity model) estimates the extra cost incurred by the whole system in case of spreading SFR in the Avon region. Model 3 runs recursively with Model 2; such that Model 3 simulates the spread of SFR and Model 2 estimates the additional incurred costs as a result of infestation with SFR of pests.

Assumptions of Models1and 2 are as follows:

(A1) Wheat supply at farm-level and wheat demand at port are assumed to be exogenous.
(A2) Due to the significant number of variables in the 2 models (1 and 2); Model 1 and 2 count only for a single year divided between three periods: harvest, storage and clearance. The harvest period extends from November to February and represents the peak period. The rest of the year represents the off-peak period and is divided between storage period (March to May) and clearance period (June to October).
(A3) It is assumed that wheat that flows through the system is homogenous. In reality, there exist multiple types and grades of wheat.
(A4) Transport, storage and biosecurity costs are all constant per unit; in other words, cost curves are linear and marginal costs are

Table 1. Variable definitions for Model 1.

Variable	Definition	Comment
$Q_{fr,t}$	Quantity transported from farm *f* to receival site *r* at time *t* (t=1 (harvest), 2 (storage), 3 (clearance)	
$Q^{s}_{f,t}$	Tonnes of grain stored on-farm *f* in period *t*	
$Q^{a}_{r,t}$	Tonnes of grain allocated to receival site r in period *t*	
$Q^{smax}_{f,t}$	Maximum storage capacity on-farm *f* in tonnes in *t*	Australian Bureau of Statistics (ABS) estimates, 2010
Q_f	Initial harvest (as area of wheat planted a_f times yield per ha) $Q_f = a_f y_f$	Based on shire crop areas and shire yields (Source: ABS 2010). Farm sizes and location given by unlabelled property ownership data (Source: DAFWA). Bushland areas excised from properties to give arable land (Source: BRS/DAFWA)
$c^{m}_{fr,t}$	Cost per tonne of transporting grain from farm *f* to receival site *r* during time *t*	Estimated from ArcGIS distance from farm centroid to receival site (Road network data source: Landgate). Estimated charges per tonne are adjusted from Road Freight Transport Industry Council estimates
$c^{s}_{f,t}$	Farm cost of storage per tonne. Includes interest foregone for one period	
$c^{b}_{f,t}$	Farm biosecurity cost of fumigating one tonne of grain over a single period	
$p^{w}_{r,t}$	Price paid to farmers for grain delivered to receival site r during period *t* (net of any delivery and service charges)	

All quantities are given in tonnes.

constant. Transport cost is higher during harvest than the other periods to reflect an increase in the demand for haulage.

(A5) The farms optimal transport and storage problem (Model 1) is separable across farms and can be determined by N separate farm optimization; where N is the number of grain farms in the region.

Model 1 farm to receival site

Model 1 represents the decisions of farmers to store or send wheat to a particular receival site by road. Wheat produced can either be stored temporarily on-farm, or transported by road to a nearby receival site either for storage or transport to port. Farms are assumed to only store wheat during the first two periods: the harvest and storage period, and to clear remaining stored wheat during the last period; the clearance period. This is to ensure that storage bins are empty and ready for new year harvest. This is given that storage capacity at farms can only receive 19% of the total harvest of wheat. The objective of the model is to maximise farmer's profit by minimizing the total costs of transporting, storing, and fumigating wheat quantities. The model is used to predict the spatial distribution of grain through time at farm and at receival sites.

The model is constrained with farms' storage capacity, road transportation cost, and storage and biosecurity costs. Wheat price received by farmers is assumed to increase by 10% from one period to the subsequent one to reflect the expected increase in prices (modified from the Australian Crop Report, 2007). Variables used in Model 1 are given in Table 1.

The farmer's profit maximisation problem is:

$$Maximize\ \pi_f$$
$$=\sum_r \sum_t (p^{w}_{r,t} - c^{m}_{fr,t}) Q_{fr,t} - \sum_{t\in 0,1} (c^{s}_{f,t} + c^{b}_{f,t}) Q^{s}_{f,t}$$

With respect to: $Q_{fr,t}\ ,Q^{s}_{f,t} \geq 0$ (1)

where $p^{w}_{r,t}$ is the farm gate price of wheat, $Q_{fr,t}$ is the quantity transported from farms to receival sites and $c^{m}_{fr,t}$ is the cost of road transport per tonne. The second term represents cost at farms of storing Q^{s}_{ft} during harvest and storage periods c^{s}_{ft} plus the biosecurity cost c^{b}_{ft} for on-farm fumigation activities to protect wheat from pest infestations while being stored on-farms. Fumigation costs depend on the duration of the storage period. The fumigation cost is based on the following assumptions:

1. Each receival site is divided into a number of storage bins: horizontal (shed-types sealed storages), bunkers (OBH) and silos (SIL).
2. For each storage bin type, there is an effective treatment to be used. Fumigation types used are Vaporphos (phosphine in vapour state), blankets (phosphine contained within a blanket form that is added over open bunkers), tablets (phosphine in tablet form) and cylinders (cylinders of phosphine).
3. The number of kilograms, blankets or cylinders of phosphine applied to each storage bin type according to the storage duration is multiplied by the unit cost (Personal communication with Ernestos Kostas of CBH).

The specific constraints for each farm are as follows:

Initial stock at each farm at t = 0: $Q_f = a_f y_f$ (2)

That is the wheat harvested is the area of wheat a_f times the yield per hectare y_f.

Equilibrium at farms: $Q_f = \sum_r \sum_t Q_{fr,t} + Q^{s}_{f,t}$ (3)

All wheat produced at each farm is either transported by road to receival sites or stored on farm.

Farm's storage capacity: $Q^{s}_{f,t} \leq Q^{smax}_{f,t} \ \forall t$ (4)

This constraint indicates that for any period of time, wheat quantities stored on each farm should not exceed the farm's storage capacity for that period.

Storage on each farm during periods

t=1,2: $Q^{s}_{f,t} = Q^{s}_{f,t-1} - \sum_r Q_{fr,t-1}$ (5)

That is, initial stock on each farm during the first and second periods is the amount stored from the previous period.

Grain allocated to receival sites in a period is

$\sum Q^{a}_{r,t} = \sum_f Q_{fr,t} \ \forall r, \forall t$ (6)

The quantity of grain allocated by all farms to recieval sites during period t is $\sum Q^{a}_{r,t}$.

Model 2 receival site to port

Wheat delivered from farms to receival sites represents the initial stock at receival sites and can either be stored temporarily at receival sites or moved immediately by rail/road to Kwinana port for further storage or export. The objective of the model is to minimise the Cooperative Bulk Handler's (CBH) cost by finding the optimal combination of costs accompanied with wheat movement and storage starting at receival sites and ending at Kwinana port. The model does not allow storage during the clearance period at receival sites to ensure all wheat is delivered to Kwinana port by the end of the year.

The model differentiates between types of wheat storage bins (Table 2) used at receival sites and port through various biosecurity costs and capacities. Table 3 gives the variables used in model 2.

The quantities of wheat committed to transportation between receival sites and port, together with allocations to storage bins represent the decision variables in the system and constitute the cost minimisation problem. Accordingly, the grain handler's cost minimisation problem is:

$$Minimize\ C_r = \sum_r \sum_t (c^{s}_{r,t} + c^{b}_{r,t}) Q^{s}_{r,t} + \sum_r \sum_{r^o} \sum_t (c^{m}_{rr^o,t} + c^{h}_{rr^o,t}) Q_{rr^o,t}$$

$$+ \sum_r \sum_t c^{m}_{rp,t} Q_{rp,t} + \sum_t (Q^{s}_{p,t} + c^{b}_{p,t})\, Q^{s}_{p,t}$$

With respect to: $Q^{s}_{r,t}, Q^{s}_{p,t}, Q_{rr^o,t}, Q_{rp,t} \geq 0$ (7)

The first term represents the storage c^{s}_{rt} and biosecurity c^{b}_{rt} costs for storing wheat at receival sites $Q^{s}_{r,t}$. The second term represents wheat transport costs $c^{m}_{rr^o,t}$ of moving wheat between receival *r* and receival site *r^o^* sites $Q_{rr^o,t}$. The handling costs $c^{h}_{rr^o,t}$ relate to moving wheat from low quality to high quality storage to treat a SFR infestation. This parameter links Model 2 to the biosecurity model; Model 3. The third term represents wheat transport and handling costs between receival sites and Kwinana port. The fourth term represents the storage and biosecurity costs of wheat stored at Kwinana port.

CBH costs are minimized subject to the following constraints:

Storage Capacity at Receival Sites: $Q^{s}_{r,t} \leq Q^{smax}_{r,t}$ (8)

Storage Capacity at Port: $Q^{s}_{p,t} \leq Q^{smax}_{p,t}$ (9)

Wheat quantities stored at receival sites and port should not exceed their storage capacity.

Equilibrium stock stored at the end of period t at receival site r:

$$Q^{s}_{r,t} = Q^{a}_{r,t} + Q^{s}_{r,t-1} - \sum_{rr^o} Q_{rr^o,t} - Q_{rpt} \quad (10)$$

Where grain stored at receival site *r* during period *t*, $Q^{s}_{r,t}$ is equal to the initial deliveries from farm during the same period $Q^{a}_{r,t}$ determined by Model 1 plus the stocks from previous period $Q^{s}_{r,t-1}$, minus wheat quantities delivered to other receival sites or port.

In model 2, storage bins at recieval sites are subdivided as follows: Horizontal bins (HOR) with concrete half walls and steel roofing with a capacity from 10,000 t to 28,000 t; High capacity horizontal bins (HRC) from 60,000 t to 275,000 t; Unsealed open bunker (OBH) storage facility; circular storage (CIR) with either steel or concrete walls; and sealed vertical silos (SIL). In the

Table 2. Variable definitions for Model 2.

Variable	Definition
$Q_{rp,t}$	Quantity transported from receival sites *r* to Kwinana port *p* at time *t=1,2,3*
$Q_{rr^o,t}$	Quantity transported between receival site *r* and r^o in case of storage capacity limitations at time *t=1,2,3* or low storage quality at *r*
Q^s_{rt}	Quantity stored at receival sites *r* during period *t*
Q^s_{pt}	Quantity stored at Kwinana port *p* during period *t*
Q^{smax}_{rt}	Maximum storage capacity at receival sites *r* during *t*.
Q^{smax}_{pt}	Maximum storage capacity at Kwinana port *p* during *t*
Q^e_{pt}	Quantity exported at Kwinana port *p* at time *t*
$c^m_{rr^o,t}$	Transport cost per tonne between receival sites *r* and r^oat time *t*, using mode of transport *m (road or rail)*
$c^m_{rp,t}$	Transport cost per tonne between receival sites *r* and port at time *t* and using mode of transport *m (road or rail)*
c^h_{rt}	Handling cost per tonne at receival sites *r*attime *t*
c^h_{pt}	Handling cost per tonne at Kwinana port *p* attime *t*
c^b_{rt}	Biosecurity cost per tonne at receival sites *r* at time *t*
c^b_{pt}	Biosecurity cost per tonne at Kwinana port *p* at time *t*
c^s_{rt}	Storage cost per tonne at receival sites *r* at time *t*
c^s_{pt}	Storage cost per tonne at Kwinana port *p* at time *t*

All quantities are given in tonnes.

Table 3. Variable definitions for Model 3.

Symbol	Description	Unit	Value/functional form
C_{EB}	Extra biosecurity cost	$	[1.5, 2, 3,4]$c^h_{r,r^o,t}$
F_I	Number of infested farms		
T	Length planning horizon	Years	T = [1,2,…….20]
γ	Rate of spread of outbreaks/pests	Km	R = [0.1,0.2,…5]
d	Distance between *f* and F_I	Km	

analysis of biosecurity bins (Model 3), HOR, HRC, OBH and CIR are classified as low-quality bins (LQBs); while sealed silos (SIL) is classified as high-quality bins (HQBs).

Model 3 grain biosecurity

The grain biosecurity model predicts the incremental biosecurity cost incurred by the wheat supply network when a strong-form phosphine resistance SFR[3]of stored grain pest emerges on a farm. The additional cost incurred by the network increases the biosecurity and handling costs c^b_{rt}, c^h_{rt}in Model 2. Model 3 accounts for the increase in the number of infested farms when outbreaks are able of spread across the wheat network by a jump-diffusion process. Notations and definitions for the biosecurity model are given in Table 3.

Outbreaks of SFR originate on farms with low-quality storage bins (LQBs) where phosphine applications do not eradicate all pests. Meanwhile, infested wheat is transported to receival sites which lead to the spread of infestation with SFR pests to CBH receival sites.

When wheat reaches the receival sites, it is sampled for pest's

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[3] Strong form Phosphine Resistance (SFR) is assumed when the outbreak is not killed by the normal applied quantity of phosphine.

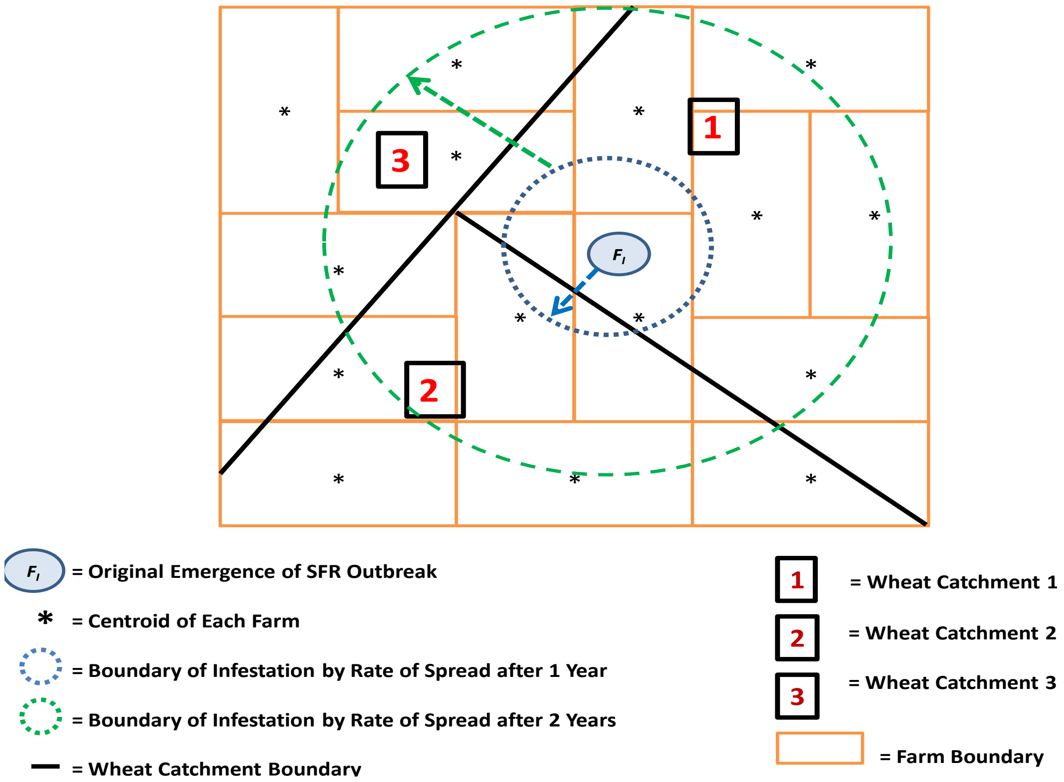

Figure 2. Spread and Jump-Diffusion of SFR outbreaks across neighbouring wheat catchments in Avon Region. Source: Authors.

detection. If the chosen sample represents the true quality, then wheat will be sent to the appropriate type of storage bins accordingly. However, if the sample does not represent the true quality, then some unrecognized infested wheat might be sent to low-quality bins (LQB). The fumigation at the LQB might kill WFR pests and leave a higher proportion of SFR to breed; which will increase the infestation level at the end. Knowing that the CBH depends heavily on LQB types as OBH and HOR (90%) (Personal communication with Ernestos Kostas from CBH) for storing wheat, can clarify the problem; the whole bulk amounts might be infested accordingly. Hence, an extra biosecurity cost (C_{EB}) is incurred to unload wheat from LQBs to HQBs for further treatments and to ensure full eradication of pests.

In addition to SFR pest spread from farm to receival sites, outbreaks spread to neighbouring farms and across the wheat network; resulting in more infested farms. We based our model on a dispersal rate of spread (Rt) mentioned in Ching'oma (2006) and supported by Shigesada et al. (1995). This process is illustrated in Figure 2.

Here, we assume simple Gaussian local dispersal on average across the grain network, and focus on the economics of contagion both locally and from farm to grain receival site. The innovation of this paper is that the biological process of pest spread has been integrated with the economics in a spatially explicit manner. This is the first time this has been achieved in the grain storage scientific literature, as far as we know. During the first year, a SFR outbreak at one farm *(f)* can change it to an infested farm (F_I) which has the ability to infest the surrounding and neighbouring farms within a distance (*d*) determined by the rate of spread (*y*). This might result in increased numbers of infested farms (F_I) and overlapping of the SFR outbreaks during the first year. In the second year, the original infested farm and the surrounding -newly- infested farms (F_I) continue to spread their infested outbreaks to more neighbouring farms and this will continue during the 20-years' time horizon of the model. On a continuous scale, the number of farms with SFR outbreaks increases which results in increased biosecurity cost (C_{EB}).

The development of new SFR populations is assumed to follow a Poisson distribution. This reflects a key assumption that SFR populations develop independently at landscape scales, and depend only (for our study) on local population selection pressures due to repeated phosphine use at non-lethal dosage rates in LQBs (Ching'oma 2006). The stochastic realisation of SFR population outbreaks adds further uncertainty to the model outputs at time t=T.

Outbreaks evolve stochastically (Figure 3). Infested receival sites apply costly biosecurity measures in a farm catchment declared to have a SFR infestation. The steps of solving the model are described in Appendix 1. The model runs for 1,000 times to average the effect of the random initial location of SFR outbreaks for each combination of parameter values. The biosecurity model is implemented in the R statistical software (R Foundation for Statistical Computing, 2011) with calls to the mathematical programming Models 1 and 2 to estimate costs and optimize them.

Shigesada et al. (1995) deliver the key result that, insofar, as a local diffusion process is most definitely stochastic, that is, the time of arrival or infestation at one point of the landscape differs from the time of arrival or infestation at another, although they may be the same distance from the source point, the diffusion process can still be characterised by a mean rate of spread. This goes back to results on Gaussian diffusion processes delivered by Skellam (1951), and this is the result we rely on in developing our model. As the rate of diffusion parameter has been explored across a range of scenarios, then scenarios where infestation likelihood is low have been included in the model.

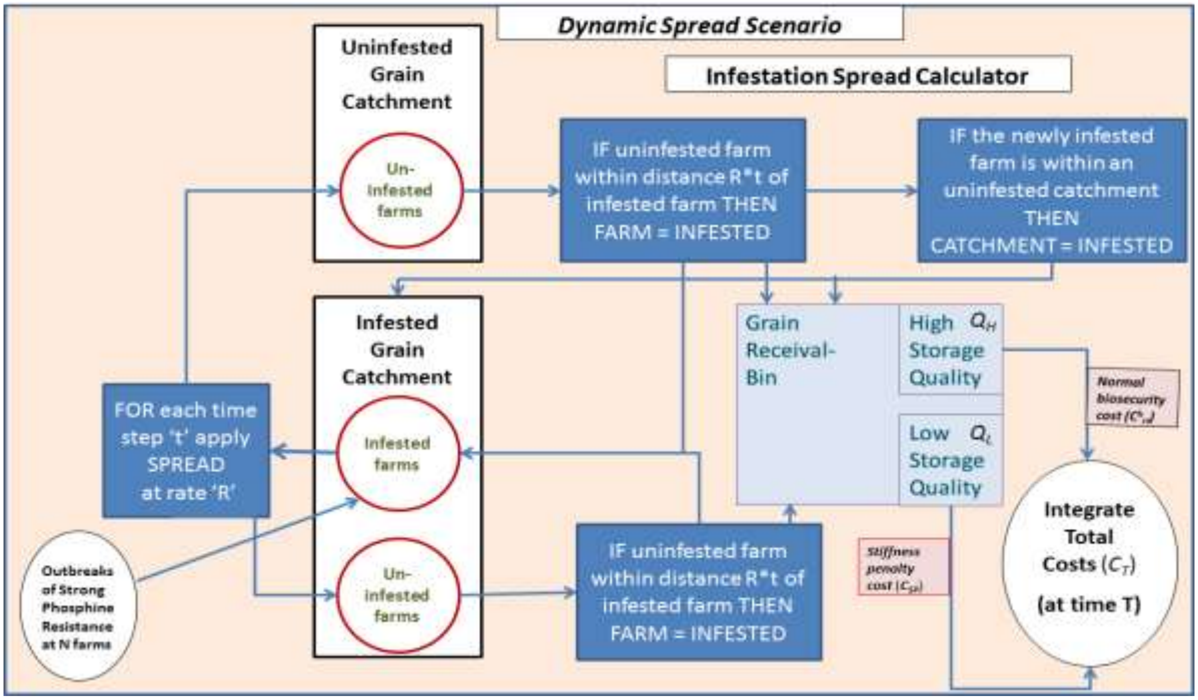

Figure 3. Overview of Model 3 grain biosecurity. Source: Authors.

Model parameters

Model 1 data

Avon region produces about 5 million tons of wheat and around 1 million ton of this quantity is stored (ABS, 2010). Quantities of wheat are delivered by road to receival sites or stored at some time on farms. ArcGIS routines are used to estimate the road distance between farms and receival sites, and wheat production per farm. There are around 6,700 wheat farms (with an area of more than 200 ha) in 38 shires within the Avon region. We have data from the WA land registry (Landgate) for 5,877 farms which were included in the model, including distances between farms and their designated receival sites, and each farm's wheat production.

Costs in Model 1

Storage costs are calculated based on a fixed cost for silos (over 25 years lifespan per unsealed silo), plus cost of unloading wheat into storage facilities and routine maintenance costs. Table 4 shows wheat storage cost and biosecurity cost and unit truck cost at farms for each period.

Maintenance cost includes cleaning, maintaining seals, etc. Additional treatments may include protectants, fungicides, or alternative fumigants.

On-farm biosecurity cost is a time-based cost that determines how much farmers to pay to protect wheat against pest infestation through aeration and fumigation. Table 4 gives biosecurity cost per ton. Farm transportation costs are costs associated with delivering wheat from farms to receival sites. The average distance (ranges between 600 m and 79 km) between each farm and the nearest receival site is then multiplied by the truck rate per unit distance before being multiplied by the number of tonnes transported.

Truck rates are higher during the harvest than the storage and clearance periods respectively; to reflect the truck congestion at receival sites. The truck rates during the harvest period also reflect the increased waiting times at receival sites, which increases truck turnaround time and increases demand for trucks.

Unit truck cost data in Table 4 is based on freight guideline rates for a 42.5 tonne prime mover with one trailer commonly used by farmers to deliver grain to receival sites, adjusted for different periods (Road Freight Transport Industry, 2007, October 2013).

Wheat price is the payment by CBH to farmers. The assumption used in the model is that the expected price increases from $220 (which is the status quo price per tonne of wheat for the year 2008 - 09) by 10% from one period to the following period.

Model 2 data

There are 26 receival sites on road and 85 receival sites on rail. Receival sites on road need to deliver wheat by road lines to other receival sites or to port. However, receival sites on rail can deliver wheat by rail or road lines to other receival sites or port. Calculations of road-transport cost have been identified earlier; while rail-transport cost has been modified from CBH data (Personal communication with Ernestos Kostas from CBH). Storage at receival sites takes place during harvest and continues until the end of the storage period. During the clearance period, all wheat is cleared from all receival sites and is delivered to Kwinana port either to be exported or stored until next year.

Time-based storage charges at receival sites -paid by CBH- are presented in the model to account for the use of storage facilities, standard grain segregation and stack management and standard grain protection; including fumigations during storage.

Storage cost at Kwinana port is included in the model for the three periods and for all storage facilities. It is assumed that wheat storage cost at receival sites and at port are the same for each time period (Personal communication with Ernestos Kostas from CBH). The gradual increase in storage cost between periods is justified by the longer duration of the third (for 3 periods; whole year), second

Table 4. Wheat storage and transport cost.

Storage cost/tonne	Time-Period 1	Time-Period 2	Time-Period 3
Silo price	1.71	1.28	2.14
Installation cost	0.27	0.20	0.33
Maintenance cost	1.67	1.25	2.08
Total storage cost for farmer/t	3.64	2.73	4.55
Aeration cost	0.27	0.20	0.33
Phosphine treatments	0.16	0.12	0.20
Additional treatments in case of infestation	0.44	0.33	0.55
Total biosecurity cost for farmer/t[1]	0.87	0.65	1.08
Truck Cost/tonne/km[2]	0.053	0.051	0.047

1- Adapted from Taylor and Dibley (2009); 2- Road Freight Transport Industry (2007, in October 2013).

Table 5. Biosecurity unit cost for different fumigation types.

Fumigant type	Blankets	Cylinders	Tablets	Vaporphos
Unit Cost	$ 85/blanket	$265/cylinder	$7.5/kg	$115/kg

Source: Personal communication with Ernestos Kostas from CBH.

(for 2 periods; 1 and 2) and first (for period 1 only) periods respectively. The Unit Storage Cost at Receival Sites and Port is assumed to be $1.3, $3.9 and $8.6 during T1, T2 and T3 respectively.

Biosecurity cost is the cost of protecting wheat quality against pests' infestation by using fumigations. Different biosecurity costs are incurred at various receival sites and at different storage bin types during the three periods. The fumigation costs are based on the following assumptions:

Each receival site is divided into a number of storage bins: horizontal (HOR), bunkers (OBH) and silos (SIL). For each storage bin type, there is an effective treatment to be used. Fumigation types used are Vaporphos (phosphine in vapour state), blankets (phosphine blankets are placed on the bunker and then covered with a tarp), tablets (phosphine in tablet form) and cylinders (cylinders of phosphine).

The number of kilograms, blankets or cylinders of Phosphine applied to each storage bin type is multiplied by the unit cost of the formulation type (Personal communication, Ernestos Kostas of CBH).

Biosecurity cost at port is included in the model for the three periods. The model differentiates between types of storage facilities in terms of biosecurity costs. The same steps are used to calculate fumigation costs by bin type at port and for the three periods. Table 5 gives unit costs for fumigation types at receival sites and port. The storage bin requires the same amount of fumigation regardless volume proportion occupied by grain. For example; according to the SIROFLO®label, effective fumigation of grain needs 1.5 tablets per cubic metre of total storage capacity (The State of Queensland, 2010).

The cost of loading and unloading wheat at receival sites and port is estimated at $3.2 per tonne across different receival sites and port for the three periods (Personal communication, Ernestos Kostas of CBH). Transportation cost at receival sites represent road and rail costs associated with transporting wheat between receival sites. The transportation cost is a distance-based cost. Most of the receival sites are found to be located within a distance range of 200 to 300 km from Kwinana port. The model differentiates between receival sites on road and on rail. Movement between receival sites on road and rail is allowed in the model. Hence, as it is cheaper to use rail transport, receival sites located on rail lines use rail transport, while receival sites away from rail lines use road transport. This means that around three quarters of wheat is delivered by rail and only limited quantity is delivered by road.

Port transportation cost is the cost of transporting wheat from various receival sites on rail/road to Kwinana port during all periods. The minimum, maximum and average transport cost between receival sites and port is around $2.42, $30 and $17.86 per tonne per kilometre respectively (Personal communication, Ernestos Kostas of CBH).

Model 3 data

Model 3 static: The key parameters of Model 3 are the number of phosphine resistant outbreaks and the stiffness penalty multiplier. First, the number of outbreaks ranges between 0 - 1,500 in a simple sensitivity analysis; with the maximum of 1,500 representing around 22% of the total number of farms within the Avon region. This assumption means that for every 4 or 5 farms, one farm is infested by an outbreak. Hence, this ensures the cost of maintaining biosecurity reaches a maximum at the regional scale, with all farm catchments containing at least one farm with a resistant outbreak. Farms were randomly sampled with equal weighting.

Second, the stiffness penalty cost multipliers range has been chosen to be between 1.5 to 4 times the current handling costs for the grain network model. The multiplier accounts for extra handling cost if infested wheat is to be moved from unsealed to sealed bins for extra or better treatment. The extra handling costs are calculated for a combination of each penalty cost and outbreaks' number (over a fine grid). The model is static and runs for a single period of one year.

Model 3 dynamic: The parameters of the model that are directly manipulated in the dynamic model are the number of initial outbreaks (chosen randomly by R), stiffness penalty cost multipliers and rate of spread. The timeframe over which the simulations are run is fixed at t=T years, though within the model, costs at each yearly time step are tracked. The range of values assigned to each control parameter was:

1) Initial number of outbreaks: Ranges between 0 - 200 outbreaks chosen randomly by R. The maximum of 200 is less than the maximum of 1,500 for the static model, and reflects the number of outbreaks required to achieve full cost saturation when the spread of outbreaks is included.
2) Stiffness penalty cost multipliers: multipliers of current grain handling costs; ranging between 1.5 – 4 multiples of the normal handling cost; and in steps of 0.5.
3) Rate of spread (ros): Ranges between 0.1 - 5 km by step size = 0.1 (as adjusted from Ching'oma, 2006).

The model runs for 1,000 times to average the effect of the random initial location of phosphine resistant outbreaks for each combination of parameter values. The spatial spread model is implemented in the R statistical software (R Foundation for Statistical Computing, 2011). The model first defines which farms are adjacent to each other. An un-infested farm is counted as being infested by a phosphine resistant pest population whenever the centroid of an un-infested farm falls within a distance of ros (rate of spread) multiplied by t of an initial outbreak epicentre. The receival point to which an infested farm sends grain is known in advance, based on the shortest distance path between farm and receival site. Thus; receival sites that receive phosphine resistant populations are also readily identified at each time step. The R code rewrites the GAMS input file by updating the parameters of the model, and the identification of which grain catchments (that is, receival sites) are of phosphine-resistance status. When the model is simulated, the GAMS model runs through a system call from within R to compute the costs associated with the current configuration of infested farms and grain catchments. These costs are then integrated over the whole grain catchment.

RESULTS

Model 1 results

Model 1 runs for all farms and its results show that it is optimal for farmers to store wheat for some time rather than transport it directly to receival sites after harvest. Two reasons support the farmer's action. First, it is cheaper for farmers to store wheat at their farms for the first two periods and to incur biosecurity costs on-farm than to transport it directly to receival sites due to the relatively high transport cost during harvest period. The on-farm storage capacity typically prevents farms from storing the whole crop. Therefore, they tend to store up to the storage capacity and send the excess to receival sites. Second, it is assumed throughout the model that transport costs are expected to increase during harvest than storage than clearance period respectively (adjusted from Road Freight Transport Industry 2007, October 2013).

Around 80% of wheat is transported to receival sites during peak (harvest) period due to lack of storage capacity at farms. This means that around one million tonnes of wheat is stored on farms within the Avon region. The results of Model 1 show that the total profit of farmers after deducting biosecurity and transport cost is around $218 per tonne in 2008-09 data (the year of the study).

Model 2 results

Results of Model 2 illustrate the quantity stored at receival sites by bin type on road and on rail. For receival sites located on road, around 25% of wheat is stored during the harvest period and storage period (T1, T2), while around 75% of wheat is stored at receival sites on rail during the same two periods; T1 and T2. Most grain is stored in OBH (bunker) bin type, followed by HOR (horizontal) bin type. CIR bin type stores the least wheat quantity. During storage period (T2), most of the wheat quantity stored at receival sites is stored at HOR bin type, followed by OBH bin type. However, SIL (silo) and CIR bin types store the least wheat quantity during T2.

The above results show that HOR and OBH bin types are the most important storage type facilities for storing wheat quantities during both periods; harvest and storage periods. Conversely, HRC, SIL and CIR bin types store the least wheat quantity during T1 and T2. Therefore, HOR and OBH bin types are the most important storage infrastructure in the Avon region. Since HOR and OBH are considered as LQBs, the reliance on their usage increases the likelihood of SFR development (leakage = under dosing of PH3 which is repeated over a number of fumigations = increased number of resistant genes in population due to death of susceptible, which increases chance of homozygosity for resistant genes through breeding). This then would affect the international market as a result of the infested grain-status. Investment in HQB, despite the initial cost, should be a priority due to the cost penalties incurred if SFR develops and cannot be controlled (e.g. Cryptolestes until sulfuryl fluoride came on the market).

The results given in Table 6 show that the system incurs about $22.6/tonne to transport, store, handle and fumigate wheat within the Avon region. Previous results illustrate that Horizontal (HOR) and bunker (OBH) bins represent around 78% of the total available storage capacity and receive wheat from about 83% of farms for Avon region. This emphasizes how important these storage bins are to wheat network in Avon region. Table 6 also highlights the extra cost of establishing SFR on farms as compared to the extra cost of upgrading the existing LQBs and the extra cost of investing in HQBs. Although the initial cost of constructing HQBs appear to be significantly higher, the protection of millionsof tonnes of wheat against SFR and maintaining the excellent overseas reputation justifies it.

Model 3 results

Within R, the number of farms with SFR outbreaks (FI) is tracked, and each time step is used to compute the local

Table 6. Unit extra cost of upgrading current LQBs and investment in HQBs.

Description	Unit Cost ($/Tonne)	NPV of Total Cost for All Quantity Produced in Avon Region ($)	NPV of Total Cost for Total Stored Quantity in Avon Region (2008-09) ($)
Total costs of transport, storage, handling and fumigation of wheat with no outbreaks' SFR (status quo)	22.6	63,342,631	12,035,100
Average total costs of transport, storage, handling and fumigation of wheat with outbreaks' SFR	31.4	88,007,019	16,721,334
Extra cost as a result of strong phosphine resistance	***8.8***	***24,664,388***	***4,686,234***
Upgrade the current LQBs in Avon region*	37.7	105,629,443	20,069,595
Extra cost of upgrading the current LQBs as compared with total cost with outbreaks' SFR	***6.3***	***17,622,424***	***3,348,261***
Investment in HQBs in Avon region*	117.5	329,325,627	59,358,049
Extra cost of investing in HQBs as compared with total cost with outbreaks' SFR	***86.1***	***241,318,608***	***42,636,715***

* Data Source: Personal Communication with Ernestos Kostas from CBH.

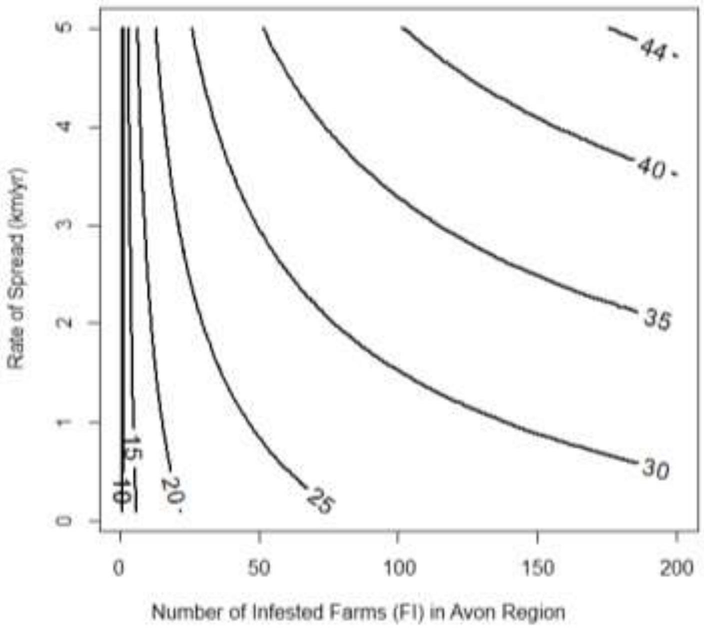

Figure 4. Extra biosecurity cost related to the infestation spread rate on farms ($million). Source: Authors' Calculations.

neighbourhood of un-infested farms (f) that fall within the population spread from an infested farm (FI) epicentre. Results of the biosecurity model show different iso-cost curves for different rates of spread and various numbers of infested farms (FI). Figure 4 illustrates the significance of the rate of spread (Rt) of SFR on the extra biosecurity cost (CEB), even with a limited number of SFR outbreaks/infested farms; FI = 200. The iso-cost curves are steep at the beginning, with just a few infested farms (FI), which shows the major effect of the rate of spread (Rt) on wheat network. Even with a small increase in the number of SFR outbreaks/infested farms (FI), the extra cost (CEB) increases at a fast rate, and can reach $44 million as a result of the rate of spread (Rt) of SFR infestations. If compared with another calculation for the extra biosecurity cost (CEB) without the introduction of the rate of spread (Rt) to the model, the extra biosecurity cost (CEB) has been reached with about 1500 infested farms (FI) rather than 200 only.

Results of the biosecurity model present a clear message; when the rate of local population spread (Rt) is high, then the development of few SFR outbreaks on farm is enough to have significant extra biosecurity cost (CEB) incurred across the whole wheat network.

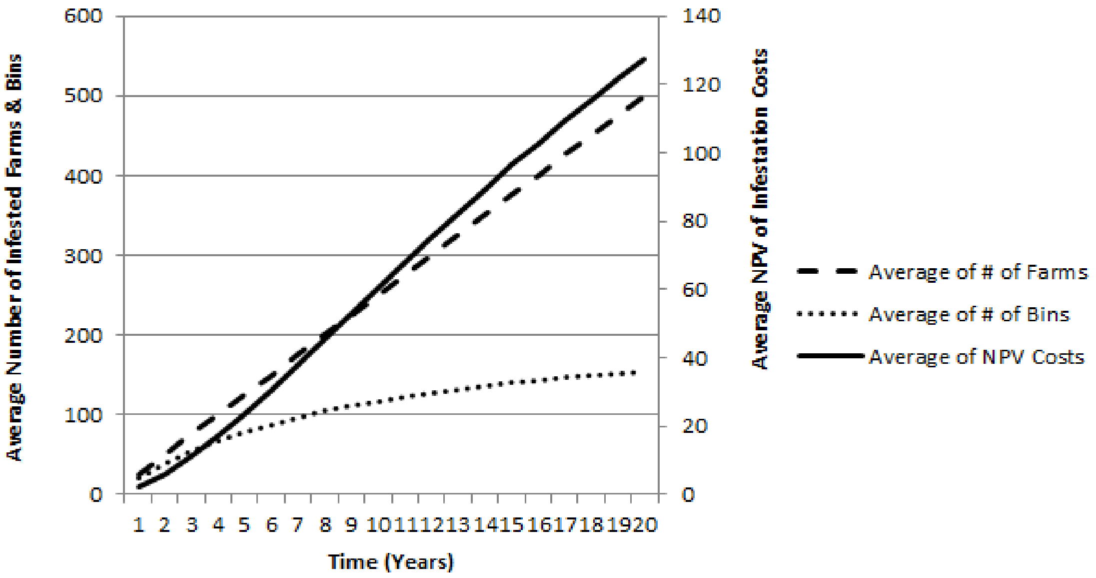

Figure 5. Average number of farms and bins and their corresponding NPV of infestation costs ($million). Source: Authors' Calculations.

Model 3 investment analysis

Model 3 is simulated for 20 years. Figure 4 illustrates the significance of the rate of spread on the extra cost associated with using LQBs, even with a limited number of outbreaks (200 only). The iso-cost curves are steep at the beginning, with a limited number of outbreaks, which shows the major effect of the rate of spread on the whole system. With number of outbreaks equals 200 or even less, the extra cost can reach significant amount as a result of the rate of spread of such infestations.

Results present a clear message; that when rate of local population spread is high, the development of few outbreaks is enough to have significant extra biosecurity costs incurred across the grain production region.

Figure 5 shows the significance of the net present value (NPV) of discount rate 5% of infestation cost on farms and receival bins over time. Notably, the NPV of storage costs increases rapidly after three years. The number of infested bins is massively increasing by progressive years and the cost of biosecurity is driven higher by an increasing number of farms infested rather than an increasing number of bins.

DISCUSSION

Results of Model 1 show that it is profitable for farmers to store wheat on farms for some time to speculate on price increases. However, storage limitation on farms forces them to send wheat directly to receival sites. Around 1 million tonnes of wheat is stored on farms for long periods of time; which could be a start for a biosecurity problem for wheat supply network; especially if farm storage is of low quality.

Model 2 gives a status quo for the total costs incurred by the CBH when wheat is not infested to be around $22.6/tonne. Also, the results illustrate how important are some types of storage bins for the wheat system; including horizontal (HOR) and bunker (OBH) bin-types which by far constitutes the significant proportion of bins used at the CBH sites. Perhaps, more investments should be made in HQBs as Silos (SIL) to lessen the probability of emergence of SFR.

The biosecurity model, Model 3, shows clearly how the number of SFR outbreaks/infested farms (FI) and their rate of spread (Rt) can have a significant effect on total cost for the entire wheat supply network. The results of the biosecurity model show that the costs incurred are around $31.4/tonne. Control of local spread of pest population may be achieved through either population eradication, change in the type of treatment and/or upgrading of LQBs to HQBs or investing in HQBs.

Investing in different types of storage facilities has different associated costs based on different investment costs illustrated in Table 6. The extra cost of upgrade of current LQBs or investment in HQB may be justified when consideration of the overseas market ($billions in trade) is taken, and that it is LQBs that are primarily responsible for the development of SFR in the first place.

Conclusion

Wheat production and export represent a major contribution to Western Australia's economy. The ability to continue as a pest and residue free wheat exporters depends largely on phosphine. The emergence of SFR within a wheat network can result in significant quality problems, extra biosecurity cost incurred by the whole system or markets' rejections of whole wheat bulks.

The results within this study show an extra biosecurity cost of $8.8/tonne incurred by a SFR outbreak over a 20 years' time horizon. The response to the appearance of SFR is highly recommended by replacing low-quality storage bins (LQBs) with sealed silos of high quality (HQBs).

Environmental Education might be one of the means of reducing such significant outbreak costs. Environmental education is concerned with the teaching of individuals and communities about the environment and its associated problems; to make them aware of the solutions to these problems, and motivated to solve them. This can be regarded as limiting or hindering the problem to arise from the very beginning. Teaching and raising awareness of farmers about how to protect and care after grain quality might solve most of the problem.

Meanwhile, the role of technological advancements' adaptation and spur might also be seen to be significant. Using current available technology can support famers' efforts by reducing efforts exerted on farms, improving grain quality and raising confidence levels in grain export levels.

Besides, the role of landowners in renting their land and maximize their annual returns (price-cost), considering that the rent (revenue – costs) and normal profits, should be encouraging to enable them to undertake an economic- agricultural/land- based activity. Since such a return is determined by many factors; including land taxation, land inelastic supply, short-term pricing fluctuation, long-term pricing rise, technological advancements, this can show a dynamic behaviour, as well as the competitive trend of interest rate available on financial markets, enabling greater future profits from income invested in the financial markets. A further research about how such factors might influence grain quality and/or incurred costs or returned rewards is highly recommended.

Conflict of Interests

The authors have not declared any conflict of interests.

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Appendix 1: Procedures for simulations on Biosecurity Model (Model 3)

Set up **parameters:**

➢ Read the co-ordinates for the set of all farms $F$from *Model 1* to assign farms' locations/coordinates in R.

➢ Read all receival sites r receiving wheat from the infested farms $F_I$which has been solved in *Model 1*.

➢ Track all receival bins' names solved in *Model 2* and ending in SIL to be HQBs, and all other names to be LQBs.

➢ Read the distance d between the -newly- infested farms $F_I$and surrounding farms f.

➢ Repeat number ofdraws**.**

Time = 1: Initially no SFR

- From all farms$F$, randomly select subset $F_I$in R to be infested with at least one SFR outbreaks or spontaneous mutation.
- From *Model 1*, infested farms$F_I$send wheat to bins at receival sites. Extra biosecurity cost applies according to:

$$C_{EB} = \begin{cases} 0, & f \not\subset \mathrm{F_I} \\ C_{EB}, f \subset \mathrm{F_I} \end{cases}$$

- *Model 2* re-runs to determine the aggregate costs.

Time = 2: Introduction of outbreaks' jump diffusion

$\mathrm{F}(R_I^t) = \begin{cases} 1, & d_f(\mathrm{R^t}) \leq \gamma \\ 0, & d_f(\mathrm{R^t}) > \gamma \end{cases}$ where γ lies between 0.1 and 5 Km.

And;

$R_I^t = R_I^{t-1} \cup f \text{ with distance } d \leq \gamma$

- From *Model 1*, infested farms F_I send wheat to bins at receival sites. Extra biosecurity cost applies according to:

$$\mathrm{C_{EB}^t} = \begin{cases} 0, f \not\subset \mathrm{F_I^t} \\ C_{EB}, f \subset \mathrm{F_I^t} \end{cases}$$

- *Model 2* re-runs to determine the aggregate costs.
- Repeat **Time = 3, …………..,20**

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