How does insect resistance to phosphine affect insect control costs of stored-grain?

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Introduction

Insect resistance to phosphine, the primary fumigant used to combat stored-grain pests, is a major problem in many countries such as Australia, Brazil, China and India (Collins et al. 2003; Rajendran 1999; Sartori and Vilar 1991; and Zeng 1999). Phosphine resistance is believed to have developed from poor fumigation practices over time, for example, multiple treatments with low insect exposure to the fumigant. (Semple et al. 1992). Once the genes responsible for resistance are present in an insect population, fumigation selects for resistance, thereby increasing the overall resistance levels in the insect population and reducing the effectiveness of phosphine (Collins et al. 2003; Collins et al. 2005; Daglish 2004; Newman 2010; Schlipalius et al. 2008). The problem of insect resistance to phosphine was compounded by the Montreal Protocol which phased out methyl bromide, the only cost effective alternative to phosphine in stored-grain management (Van Graver and Banks 1997). Although there currently are no economical alternatives to phosphine as a stored grain fumigant (Collins et al. 2005), other strategies such as integrated pest management (IPM) have been adopted to help slow the development of resistance (Lorini and Filho 2004; Mori et al. 2006). IPM combines different tools intended to reduce fumigation frequency, for example, sampling grain to determine if fumigation is necessary instead of the conventional calendar based approach of automatically treating it. When combined with aeration, sampling can reduce phosphine use and potentially minimize the development of phosphine resistance. In some countries where insect resistance is problematic, stored grain managers have had success combating resistance by using IPM (Lorini and Filho 2004; Mori et al. 2006).

Phosphine resistance in stored grain pests has reportedly been detected in the US (Bonjour 2010). This has increased concerns about stored grain management practices in the U.S.; specifically, stored grain managers have been reluctant to adopt the full range of IPM tools. This reluctance may be due in part to perceptions about IPM costs. IPM can reduce phosphine use (Lorini and Filho 2004; Mori 2006); however, Adam et al. (2010) found that some IPM strategies cost more than calendar based fumigation under many (but not all) situations. For example, IPM was found not to be a cost effective alternative to calendar based fumigation in warmer climates or when the period of grain storage is long. However, costs were only examined for a single period and could not account for other potential costs resulting from increased pest resistance. For example, an increase in pest resistance over time could lead to the need for additional fumigation. If resistance develops rapidly, there is potential for a big difference in cost between strategies that frequently fumigate and those that do not. Accounting for this potential cost is necessary for more accurate comparisons between IPM and non-IPM strategies. In this study, additional costs associated with changes in pest resistance are empirically estimated and included in the cost benefit analysis of two stored grain management strategies, IPM versus non-IPM. The overall goal is to determine how phosphine resistance of lesser grain borer (LGB), the primary pests of stored wheat and rice, affects costs of alternative approaches to stored grain insect control. The specific objectives of the research are to:

1. Determine how four different influences on resistance development affect the cost of two different stored grain management strategies, IPM and calendar based fumigation. The four different influences include (referred to as the control parameters): LGB emigration

back to the outside population, fumigation effectiveness, the average necessary frequency of fumigation and the economic threshold; and

2. Determine if the use of a positive discount rate, given the four influences on resistance development in objective one, ever result in a scenario in which in the net present value (NPV) of costs for IPM are lower than for calendar based fumigation.

Literature Review

Most researchers recognize that pest resistance is global problem (Collins et al. 2005; Laxminarayan 2003; Semple et al. 1992); however, the economical costs of pest resistance remain unclear. Many view pest susceptibility to an insecticide as a common property resource (Cowan and Gunby 1996; Hueth and Regev 1974; Fleischer 1998; Laxminarayan 2003). Depletion of the resource occurs over a long time frame and results from many firms. This makes it difficult for individual firms to internalize their contribution to the total cost. Several conceptual models have been proposed to explain how pest management strategies impact pest resistance. For example, Hueth and Regev (1974) demonstrated how farm level decision makers can influence changes in the resistance levels of a pest population. Their model included a single crop with one pest and one gene responsible for resistance. Analysis centered on the economic threshold for pesticide application, the known point when a pesticide must be used to prevent an economic loss from crop damage. They showed that the economic threshold increases in proceeding years due to decisions made in the current year. Therefore, pest resistance should be modeled dynamically because changes in resistance are the direct result of previous choices. This result was supported by Lichtenberg and Zilberman (1986) who showed that use of products resulting in product resistance increases the future amounts of product needed to achieve previous results. Increased product use means increased treatment costs.

Hurley et al. (1997) used the Hardy-Weinberg principle (which states that the presence of particular genotypes remain constant in a population unless there is a disturbance) to model optimal crop refuge size. Refuge is a designated portion of the crop land where pesticide application does not occur. The purpose of the refuge is to maintain some level of pest susceptibility as a means to control the development of pest resistance. Secchi and Babcock (1999) expanded the Hurley et al. model by including random weather elements and a minimum susceptible pest population. They found that the levels of susceptibility are significantly affected by pest mobility and the ability of refuge and non-refuge pests' to mix.

In order to accurately determine the costs associated with pest resistance, understanding the genetic mechanisms of resistance and the actual levels of resistance are necessary. Daglish (2004) identified two resistant levels to phosphine in LGB. Collins et al. (2005) found that LGB exhibiting strong resistance to phosphine had an additional mechanism not present in the weak resistant LGB. These two results led to the discovery by Schlipalius et al. (2008) that two different genes are responsible for LGB resistance. Further, the genes interact in such a way allowing the LGB to exhibit four different levels of phosphine resistance which range from about 2.5 to over 250 times the resistance of susceptible pests. These three studies are important because previous economic models assume that a single gene is responsible for resistance. Given this new information, empirical economic studies can more accurately estimate costs resulting from resistance.

Sousa et al. (2009) reported resistant LGB, in the absence of phosphine exposure, may suffer fitness costs compared to susceptible pests. In essence, fitness costs are the trade-offs that result when one genetic trait is given up for another. The fitness costs associated with resistant pests may allow previous levels of susceptibility to be regained once phosphine use is substantially reduced. Therefore, phosphine reducing strategies such as IPM may do more than slow resistance development, they may actual reverse it.

Conceptual Framework and Hypothesis

Higher frequencies of phosphine use in stored grain management result in the faster development of pest resistant LGB (Collins et al. 2005; Hueth and Regev 1974; Lichtenberg and Zilberman 1986). As the resistance to phosphine increases, more frequent applications are needed to control economic damage. This increase of phosphine use would result in greater costs. If resistance development under two pest management strategies differs enough, the strategy with the lower fumigation frequency may be more cost effective in the long run even if initial costs are higher.

> Hypothesis 1: When resistance development is high (high emigration and fumigation effectiveness) and the relative fumigation frequency of IPM is low, IPM will be more cost effective than calendar based fumigation.

Hueth and Regev (1974) demonstrated how regular use of a pesticide will diminish the insecticide susceptibility of crop pests. Similarly, fumigation with phosphine in stored grain selects for phosphine resistant pests and increases the relative proportion of resistant pests in the overall population (Collins et al. 2003; Collins et al. 2005; Daglish 2004; Newman 2010; Schlipalius et al. 2008). Hurley et al. (1997) and Secchi and Babcock (1999) explained the process by which two pest populations with different resistance levels mix.

Using the same logic, pests that are fumigated in stored grain would have higher levels of resistance compared to the population outside. When the pests inside the stored grain return to the outside, the outside population's levels of resistance would increase. Therefore, pest emigration, where pests inside the stored grain return to the outside population, will positively affect resistance development and the higher the level of emigration the faster the rate of resistance development.

> Hypothesis 2: When pests inside the storage facility emigrate in high (low) proportions relative to the outside pest population size, the cost of IPM will be more (less) attractive when compared to the cost of calendar based fumigation.

Additionally, the more pests there are inside the stored grain relative to the outside when fumigation occurs the greater the change in the outside levels of resistance when the two populations mix. Insect immigration (into the stored grain), reproduction, aeration, weather, the grain temperature and grain moisture are factors that contribute the build-up of pests inside the storage facility. In short, these factors would affect the frequency of necessary fumigations to avoid economic damage. For simplicity, frequency of necessary fumigation will be used in place of a growth model incorporating the different pest build-up factors. The fumigation frequency will be defined as the average percentage of time fumigation in necessary over a long time horizon, for example, the need to fumigate 50% of the time.

> Hypothesis 3: When fumigation frequency is high (low), the cost of IPM will be more (less) attractive when compared to the cost of calendar based fumigation.

The impact fumigation effectiveness has on resistance development will be dependent on the other factors, specifically, emigration and fumigation frequency. If these factors are very low but fumigation effectiveness is very high, only a small proportion of resistant pests (small relative to the outside population size) would mix with the larger population. In this case, resistance development would occur slowly. On the other hand, if fumigation frequency is high and emigration and fumigation frequency are also high, resistance will develop more rapidly. The lower the fumigation frequency and other factors are, the slower resistance development would occur.

> Hypothesis 4: When fumigation effectiveness is high (low) and emigration and fumigation frequency are also high (low) the cost of IPM will be more (less) attractive when compared to the cost of calendar based fumigation.

At the end of the storage period, grain is sold and removed from the storage facility. The number of fumigations per period is the only variable costs of calendar based fumigation; whereas, IMP variables costs include fumigation and sampling. As pest resistance increases the number of fumigations per period will also eventually increase so that the pest population inside the stored grain can be controlled. Under IPM, the number of samplings would also increase depending on sampling results obtained earlier in the storage period. For each strategy, the net present value (NPV) of costs under a specified time horizon and discount rate can be calculated and compared. If the rate of pest resistance development is high, and there is considerable disparity between the numbers of fumigation events of the two strategies, it is possible that the NPV of costs for IMP could be lower than that of calendar based fumigation. This would especially be true as the cost difference between fumigation and sampling was high. If there was a large enough difference, this would be true even at moderate discount rates. On the other hand, if the difference between the cost of sampling and fumigation was low and the development of resistance was also low, even at a low discount rate the NPV of costs for calendar based fumigation would be lower compared to IPM.

> Hypothesis 5: When resistance development is very high and the frequency of necessary fumigation is very low, the NPV of cost for IPM will be less than that of calendar based fumigation using a positive discount rate.

Methodology

Overview of the Stored Grain Management Simulation

Following the simulation of Adam et al. (2010), grain is received shortly after being harvested and allowed to cool. The decision as to how long the grain will be stored as well as the management strategy is made prior to receiving the grain. Once in storage, the grain is fumigated at a prescribed time (calendar-based strategy) or sampled and potentially fumigated depending on sampling results (IPM strategy). The need to fumigate (or sample) arises from a potential pest build-up inside the storage facility (determined by the fumigation frequency). At the conclusion of the storage period, grain is inspected and removed from storage. Costs incurred under each strategy include the cost of fumigation for calendar based fumigation and fumigation and sampling for IPM. For simplicity, potential costs from IDK or infestation are assumed to be zero.

An additional consideration, based Hurley et al. (1997) and Secchi and Babcock (1999), includes the possibility that pests in the stored grain emigrate back to the population outside. If fumigation has occurred and some level of resistance is present in the pest population, then pests inside the stored grain will have different levels of resistance after fumigation compared to the population outside. When grain is sold, some pests inside the stored grain facility will rejoin the outside population and change the overall resistance levels.

Simulating Changes in Resistance Levels

When the grain is received, pests are able to immigrate into the stored grain and begin reproducing. Typically, weather, state of the grain (temperature and moisture content) and the size of the storage facility are used to determine the build-up of pests in the grain. For simplicity, the frequency of necessary fumigation is used as a substitute to determine pest build-up.

Hueth and Regev (1974) described the process by which an insecticide, in this model fumigation with phosphine, selects for resistance and a new population with increased resistance remains. Their model considered a single pest with a single level of resistance. In the case of LGB, Schlipalius et al. (2008) identified four different resistance levels relative to the pests being susceptible. Since the LGB are the primary pests of stored wheat and rice and the genetic mechanism and levels of resistance are well established, the simulation will assume LGB are the only stored grain pests that have to be controlled. According to Hueth and Regev (1974), the change in resistance after fumigation can be calculated as:

$$(1) \qquad (1-F)\boldsymbol{\beta}_{\boldsymbol{i}}^{T}\boldsymbol{R} = \boldsymbol{\lambda}_{\boldsymbol{i}}$$

$$s.t.\, b_{ij} \geq l_{ij}, \forall\, ij$$

where F is the effectiveness of fumigation, $0 \leq F \leq 1$, $\boldsymbol{\beta}_{\boldsymbol{i}}$ is a vector of the proportions of the four resistance levels plus susceptibility in the population inside the stored grain at time interval *i* with elements b_{ij} for $j = 1, \ldots 5$, and $\sum_j b_{ij} = 1$, $\boldsymbol{R}_{\boldsymbol{i}}$ is a vector of the four resistance levels relative to susceptibility and includes susceptibility (which equals 1) with elements $r_{ij} \sim N(\mu_j, \sigma_j^2)$, $\boldsymbol{\lambda_i}$ is a vector of the surviving resistance level proportions in the population with elements l_{ij}, and $\sum_j b_{ij} = 1$. To allow for the next step in the process, additional growth, fumigation or the stored grain pest population to mix with the outside population, $\boldsymbol{\lambda_i}$ is standardized to 1 such that:

(2)
$$\frac{\boldsymbol{\lambda_i}}{\sum_j \lambda_{ij}} = \boldsymbol{\beta_{i+1}}$$

For additional simplicity within the simulation, immigration after fumigation is assumed not to occur.

Under IPM, sampling will occur prior to fumigation. A random number generator (the ranuni function is SAS) is used to determine if fumigation, given the fumigation frequency, is necessary. Sampling is assumed to be 100% accurate. If fumigation occurs under IPM, then the population changes is the same as describe above. If, on the other hand, fumigation is not deemed necessary then the population inside the stored grain is unchanged.

When the grain is sold and moved at the end of each period, pests within the stored grain return to the outside population,

(3)
$$\frac{\delta \boldsymbol{\beta_{i+2}} + \boldsymbol{\alpha_i}}{\sum_j \left(\delta b_{i+2,j} + a_{ij}\right)} = \boldsymbol{\alpha_{i+1}}$$

where δ is the proportion of pests inside the stored grain that return outside relative to the outside population (emigration), $0 < \delta < 1$, $\boldsymbol{\alpha_i}$ is a vector of the proportions of the four resistance levels plus susceptibility in the outside population with elements a_{ij} and $\boldsymbol{\alpha_{i+1}}$ is a vector of the new proportions of the outside population.

As resistance levels increase, the number of pests remaining after fumigation in each period will also increase. At some point, additional fumigation will become necessary. This would be the case regardless of strategy; however, one would expect pest resistance to development more quickly where fumigation occurs more frequently. Once deemed necessary, fumigation would occur twice in each period under calendar based fumigation. Under an IPM strategy, sampling would occur once or twice but fumigation may not be needed or it could occur once or twice in the period. The economic threshold is used to determine a second fumigation is necessary such that when $\sum_j^5 \lambda_{ij} \geq \tau$, where τ is the economic threshold, then additional fumigation is necessary. If more fumigation is needed, equations (1) and (2) are repeated prior to calculating equation (3).

Estimation of Costs

At the conclusion of each period, once grain has been sold, the costs under each strategy are calculated,

(4) $$SC_{kp} = C_F N_{Fp} + C_S N_{Sp}$$

where SC_{kP} is the cost of strategy *k* in period *p*, C_F and C_S are the costs of fumigation and sampling respectively and N_{FP} and N_{SP} are the number of fumigations and samplings respectively. At the conclusion of *P* periods, the net present value of cost for strategy *k*, NPV_k, is calculated and with discount rates, *d*, where

(5) $$NPV_k = \sum_{p=1}^{P} \frac{SC_{kp}}{(1+d)^p}$$

By varying the control parameters, multiple scenarios can be generated. Under any scenario, the most cost effective strategy is selected by:

(6) $$\min_k NPV_k \,|k \in \{IPM, calendar\ basedfumigation\}$$

Additionally, the marginal effects for the control parameters are estimated using maximum likelihood estimation and correcting for heteroskedasticity from the discount rate. The model estimated is:

$$NPV_{km} = \boldsymbol{\gamma_k X_{km}} + \varepsilon_{km} \quad (7)$$

where $\boldsymbol{X_{km}}$ is a vector of the four control parameters for strategy k and scenario m, $\boldsymbol{\gamma_k}$ is a vector of parameters under strategy k and ε_{km} is the random error term.

Data

In this study, four Monte Carlo type simulations are used to generate data and test the proposed hypotheses. The four pest resistance levels are from Schlipalius et al. (2008), but are allowed to be normally distributed (the susceptible level is set to 1 with 0 variance). The starting values for the resistance levels for susceptible weak 1, weak 2, moderate and strong were 0.9405, 0.0586, 0.0004, 0.0004 and 0.0001 respectively. The means for the weak 1, weak 2 and moderate resistance levels were calculated as the average of the ranges for each resistance level (see Schlipalius et al. 2008) and the standard deviation were calculated as 90% of 1/6th of total range. The mean used for strong resistance was 500 and variance used was 75. Cost of fumigation and sampling values are from Adam et al. (2010). The control parameters in the simulation including emigration, fumigation frequency, fumigation effectiveness, and economic threshold as well as the discount rate were varied to generate different results. In each simulation, parameters are specified and 1000 samples of a 50 year time horizon (50,000 total observations) were generated for each strategy (IPM and calendar based fumigation). The NPV of costs under each strategy were calculated and then averaged across the 1000 samples. Four different simulations were conducted resulting in four sets of results (one group for each simulation). In each simulation, the control parameter was varied by two levels, except for fumigation effectiveness which varied over three levels, giving a total of 48 scenarios under each simulation. A total of 2.4 million observations (50 year period X 1000 samples X 48 different scenarios) were generated for each simulation. Simulations 1 and 3 differ only by the economic threshold used as do simulations 2 and 4.

Results

The results for simulations 1-4 are shown in Tables 1-4 respectively. The marginal effects of the control parameters for calendar based fumigation and IPM are shown in Tables 4-8. In Figures 1-8, the period cost per tonne ($) are overlaid on the development of resistance to demonstrate how the proportional changes in resistance levels affect costs. From Tables 1-4, the general trend appears that when the frequency of fumigation for IPM is much lower than that of calendar based fumigation (in most cases less than 75%) IPM is the more cost effective strategy over time. These results are similar to Adam et al. (2010) who found that at lower levels of pest build-up (low immigration or cooler climates), IPM with sampling is more cost effective than calendar based fumigation. The results in this study also show this is the case regardless fumigation effectiveness and even when the discount rates are moderate. It is also apparent that in the cases when calendar based fumigation is more cost effective than IPM, as emigration increases and when the fumigation frequency is less than 100%, the difference between IPM and calendar based fumigation decreases. In some cases the differences are very small. This may make choosing the best strategy more difficult. There is a special case where the combination of low emigration and a low discount rate make IPM more cost effective even at a higher fumigations frequency. It is also interesting to note that when the economic threshold is reduced from 0.4 to 0.25 (Tables 3 and 4), costs are increased across all strategies and scenarios but the trends identified in this section do not change.

The effect of fumigation effectiveness is not easily observed from Tables 1-4; however, the estimated marginal effect under each strategy indicates fumigation effectiveness has a negative relationship with cost, the higher the fumigation effectiveness the lower the NPV of cost. This relationship is made clearer by examining the relationship between the development of resistance and period costs. For example, in Figures 1 and 3 (where the only difference between the two results is the fumigation effectiveness, 95% versus 70%), the development of resistance is much lower with 70% fumigation effectiveness, but costs jump sooner. This occurs since a smaller amount of resistant pests, compared to when fumigation effectiveness is 95%, are needed to reach the economic threshold after the first fumigation. Although, higher levels of fumigation effectiveness will more rapidly increase the development of resistance once all levels of resistance are present in the pest population, the additional costs of resistance from higher fumigation effectiveness (95%) are realized later than when fumigation effectiveness is low (70%). In this scenario, managers may be able to increase fumigation effectiveness at a lower cost than additional fumigation; however, the development of resistance would be about the same. On the other hand, the slower development of resistance could be maintained by introducing technology that would inhibit pest growth (for example aeration) or shifting to IPM with sampling if the necessary frequency of fumigation was low (or a combination of both aeration and sampling). This would only be realistic if the costs of one or both of these are less than a second fumigation.

Discussion

In this study, the additional costs resulting from pest resistance were realized by the need for additional fumigation (calendar based fumigation) or by the cost of sampling and in most cases later additional fumigation (IPM). When the necessary frequency of fumigation was low, IPM was more cost effective than calendar based fumigation. Another way to consider this is that the costs of IPM were greater than calendar based fumigation at the beginning of the time horizon; however, they were less (sometimes significantly so) towards the end of the time horizon. Even at moderate discount rates (10-15%), IPM was more cost effective than calendar based fumigation. Therefore, a trade off between higher start up costs with IPM versus higher operating costs in subsequent years exists. From the simulation scenarios presented, most cases had a clear choice. If the NPV of costs were very close, the choice may not be as clear.

In order to extend the useful life of phosphine, IPM with sampling can be used to reduce the development of resistance. In order for IPM to be the optimal choice, the necessary fumigation frequency must be reduced from 100% to a level low enough to make IPM cost effective. Aeration is one alternative that can potentially reduce the need to fumigate, but this may not be as effective in warmer climates. In the cases where the cost effectiveness of IPM is very close to that of calendar based fumigation, incentives to use IPM with sampling may be necessary.

A Monte Carlo type study was used to simulate the development of pest resistance and the subsequent increases in cost. This simulation had a number of limitations. First, the control parameters, specifically fumigation effectiveness, frequency of fumigation, and emigration were held constant. Further, the fumigation effectiveness was a simplified proxy for immigration and growth. Second, where sampling was used, it was assumed to be

100% effective. Third, costs were fixed and limited to only fumigation and sampling. One suggestion for further research is to expand the simulation with more realistic control parameters and allow them to be stochastic. Another potential area for research would be to explore how grain managers risk aversion would impact the selection of the tradeoff between high start up costs versus higher operating costs down the road.

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Table 1. Simulation 1 of Grain Management Cost, Economic Threshold = 0.40

IPM	Calendar Based	Fumigation Frequency	Fumigation Effectiveness	Emigration Rate	Discount Rate
21.176	15.483	1.00	0.95	0.40	0.10
15.773	15.481	0.75	0.95	0.40	0.10
10.843	15.465	0.50	0.95	0.40	0.10
22.618	16.528	1.00	0.70	0.40	0.10
16.948	16.531	0.75	0.70	0.40	0.10
11.699	16.528	0.50	0.70	0.40	0.10
14.635	10.693	1.00	0.95	0.05	0.10
11.531	10.693	0.75	0.95	0.05	0.10
8.837	10.692	0.50	0.95	0.05	0.10
15.767	11.521	1.00	0.70	0.05	0.10
12.117	11.522	0.75	0.70	0.05	0.10
8.926	11.520	0.50	0.70	0.05	0.10
92.906	67.891	1.00	0.95	0.40	0.01
71.071	67.907	0.75	0.95	0.40	0.01
49.359	67.886	0.50	0.95	0.40	0.01
95.218	69.591	1.00	0.70	0.40	0.01
73.890	69.590	0.75	0.70	0.40	0.01
51.337	69.595	0.50	0.70	0.40	0.01
67.574	49.420	1.00	0.95	0.05	0.01
47.043	49.408	0.75	0.95	0.05	0.01
32.062	49.422	0.50	0.95	0.05	0.01
77.078	56.334	1.00	0.70	0.05	0.01
55.777	56.309	0.75	0.70	0.05	0.01
35.524	56.323	0.50	0.70	0.05	0.01

Table 2. Simulation 2 of Grain Management Cost, Economic Threshold = 0.40

IPM	Calendar Based	Fumigation Frequency	Fumigation Effectiveness	Emigration Rate	Discount Rate
12.882	11.117	0.85	0.85	0.60	0.15
9.925	11.106	0.65	0.85	0.60	0.15
5.904	11.110	0.35	0.85	0.60	0.15
17.059	14.354	0.85	0.60	0.60	0.15
13.579	14.354	0.65	0.60	0.60	0.15
8.627	14.354	0.35	0.60	0.60	0.15
10.917	9.404	0.85	0.85	0.20	0.15
8.416	9.394	0.65	0.85	0.20	0.15
5.297	9.403	0.35	0.85	0.20	0.15
17.092	14.354	0.85	0.60	0.20	0.15
13.673	14.354	0.65	0.60	0.20	0.15
8.491	14.354	0.35	0.60	0.20	0.15
37.805	32.172	0.85	0.85	0.60	0.05
29.537	32.187	0.65	0.85	0.60	0.05
17.367	32.187	0.35	0.85	0.60	0.05
42.862	35.922	0.85	0.60	0.60	0.05
34.568	35.922	0.65	0.60	0.60	0.05
21.449	35.922	0.35	0.60	0.60	0.05
34.065	29.302	0.85	0.85	0.20	0.05
26.097	29.323	0.65	0.85	0.20	0.05
15.061	29.322	0.35	0.85	0.20	0.05
42.608	35.922	0.85	0.60	0.20	0.05
34.198	35.922	0.65	0.60	0.20	0.05
21.558	35.922	0.35	0.60	0.20	0.05

Table 3. Simulation 3 of Grain Management Cost, Economic Threshold = 0.25

IPM	Calendar Based	Fumigation Frequency	Fumigation Effectiveness	Emigration Rate	Discount Rate
22.755	16.643	1.00	0.95	0.40	0.10
17.074	16.639	0.75	0.95	0.40	0.10
11.764	16.629	0.50	0.95	0.40	0.10
27.964	20.438	1.00	0.70	0.40	0.10
21.869	20.438	0.75	0.70	0.40	0.10
15.940	20.438	0.50	0.70	0.40	0.10
16.163	11.802	1.00	0.95	0.05	0.10
12.266	11.805	0.75	0.95	0.05	0.10
8.992	11.803	0.50	0.95	0.05	0.10
27.964	20.438	1.00	0.70	0.05	0.10
21.960	20.438	0.75	0.70	0.05	0.10
15.769	20.438	0.50	0.70	0.05	0.10
95.410	69.706	1.00	0.95	0.40	0.01
73.513	69.745	0.75	0.95	0.40	0.01
51.713	69.715	0.50	0.95	0.40	0.01
101.504	74.188	1.00	0.70	0.40	0.01
80.126	74.188	0.75	0.70	0.40	0.01
57.441	74.188	0.50	0.70	0.40	0.01
79.083	57.827	1.00	0.95	0.05	0.01
57.622	57.824	0.75	0.95	0.05	0.01
36.869	57.870	0.50	0.95	0.05	0.01
101.504	74.188	1.00	0.70	0.05	0.01
79.418	74.188	0.75	0.70	0.05	0.01
57.376	74.188	0.50	0.70	0.05	0.01

Table 4. Simulation 4 of Grain Management Cost, Economic Threshold = 0.25

IPM	Calendar Based	Fumigation Frequency	Fumigation Effectiveness	Emigration Rate	Discount Rate
14.651	12.519	0.85	0.85	0.60	0.15
11.417	12.507	0.65	0.85	0.60	0.15
6.776	12.518	0.35	0.85	0.60	0.15
17.059	14.354	0.85	0.60	0.60	0.15
13.579	14.354	0.65	0.60	0.60	0.15
8.627	14.354	0.35	0.60	0.60	0.15
13.686	11.717	0.85	0.85	0.20	0.15
10.526	11.699	0.65	0.85	0.20	0.15
6.180	11.711	0.35	0.85	0.20	0.15
17.092	14.354	0.85	0.60	0.20	0.15
13.673	14.354	0.65	0.60	0.20	0.15
8.491	14.354	0.35	0.60	0.20	0.15
40.216	33.985	0.85	0.85	0.60	0.05
31.773	33.990	0.65	0.85	0.60	0.05
19.148	33.993	0.35	0.85	0.60	0.05
42.862	35.922	0.85	0.60	0.60	0.05
34.568	35.922	0.65	0.60	0.60	0.05
21.449	35.922	0.35	0.60	0.60	0.05
38.862	32.986	0.85	0.85	0.20	0.05
30.411	33.007	0.65	0.85	0.20	0.05
18.037	33.013	0.35	0.85	0.20	0.05
42.608	35.922	0.85	0.60	0.20	0.05
34.198	35.922	0.65	0.60	0.20	0.05
21.558	35.922	0.35	0.60	0.20	0.05

Table 5. Marginal Effects of Control Parameters for Calendar Based Fumigation

Parameter	Estimate	Standard Error	t Value	p Value
Fumigation Effectiveness	-19.4561	4.2542	-4.57	0.0001
Fumigation Frequency	-3.2591	2.6425	-1.23	0.2241
Emigration	11.1392	2.7314	4.08	0.0002

Note economic threshold = 0.4

Table 6. Marginal Effects of Control Parameters for IPM

Parameter	Estimate	Standard Error	t Value	p Value
Fumigation Effectiveness	-20.1861	5.0881	-3.97	0.0003
Fumigation Frequency	18.5759	3.1603	5.88	0.0001
Emigration	10.6065	3.2669	3.25	0.0023

Note economic threshold = 0.4

Table 7. Marginal Effects of Control Parameters for Calendar Based Fumigation

Parameter	Estimate	Standard Error	t Value	p Value
Fumigation Effectiveness	-19.3931	3.1022	-6.25	0.0001
Fumigation Frequency	-2.2241	1.9265	-1.15	0.2547
Emigration	6.2108	1.9923	3.12	0.0032

Note economic threshold = 0.25

Table 8. Marginal Effects of Control Parameters for IPM

Parameter	Estimate	Standard Error	t Value	p Value
Fumigation Effectiveness	-21.1700	4.0005	-5.29	0.0001
Fumigation Frequency	21.5158	2.4843	8.66	0.0001
Emigration	5.8795	2.5692	2.29	0.0271

Note economic threshold = 0.25

Figure 1. Period Cost/Tonne & Resistance Development for Calendar Based Fumigation (Fum. Effect. = 0.95, Emigrate = 0.05)

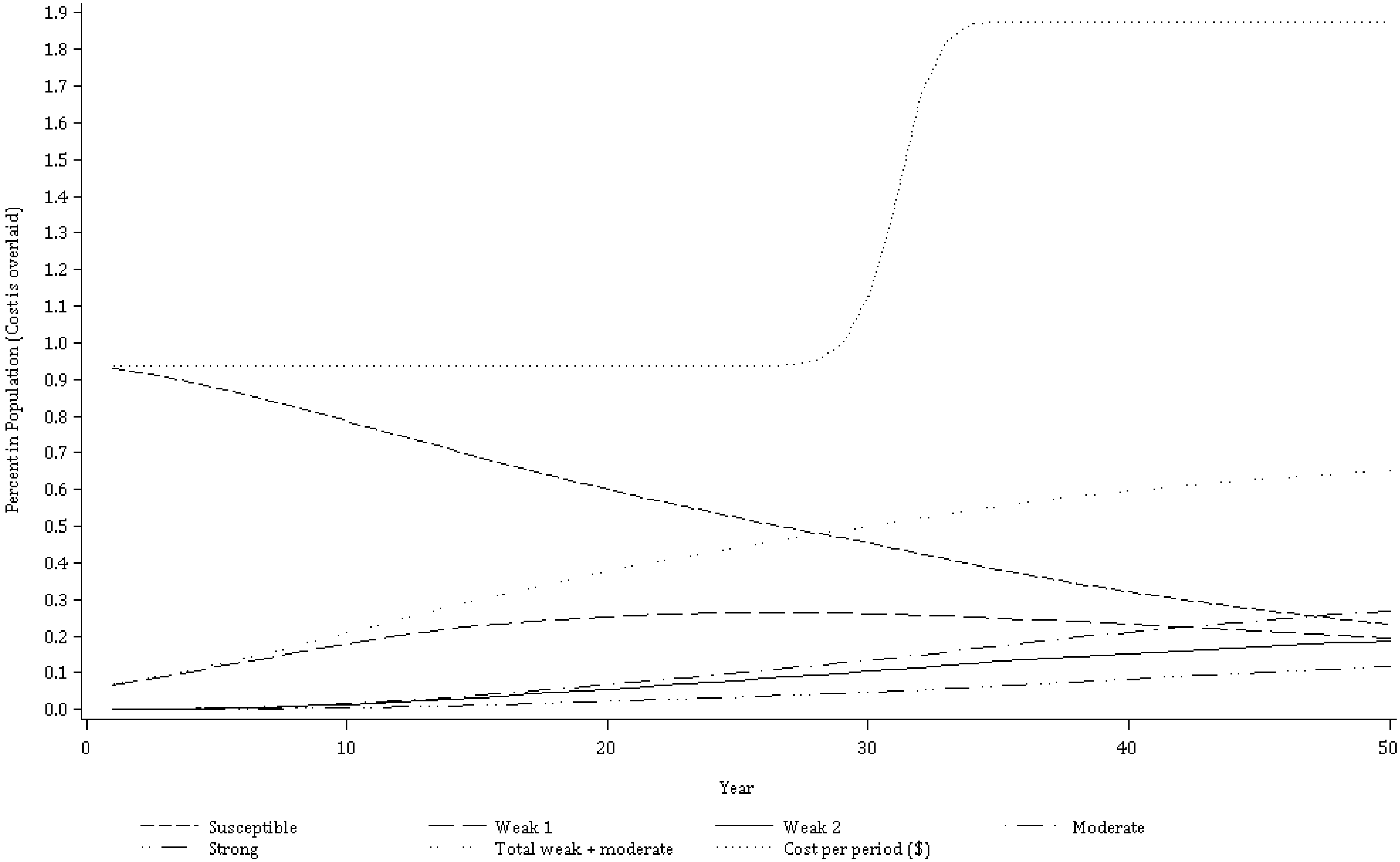

Figure 2. Period Cost/Tonne & Resistance Development for Calendar Based Fumigation (Fum. Effect. = 0.95, Emigrate = 0.4)

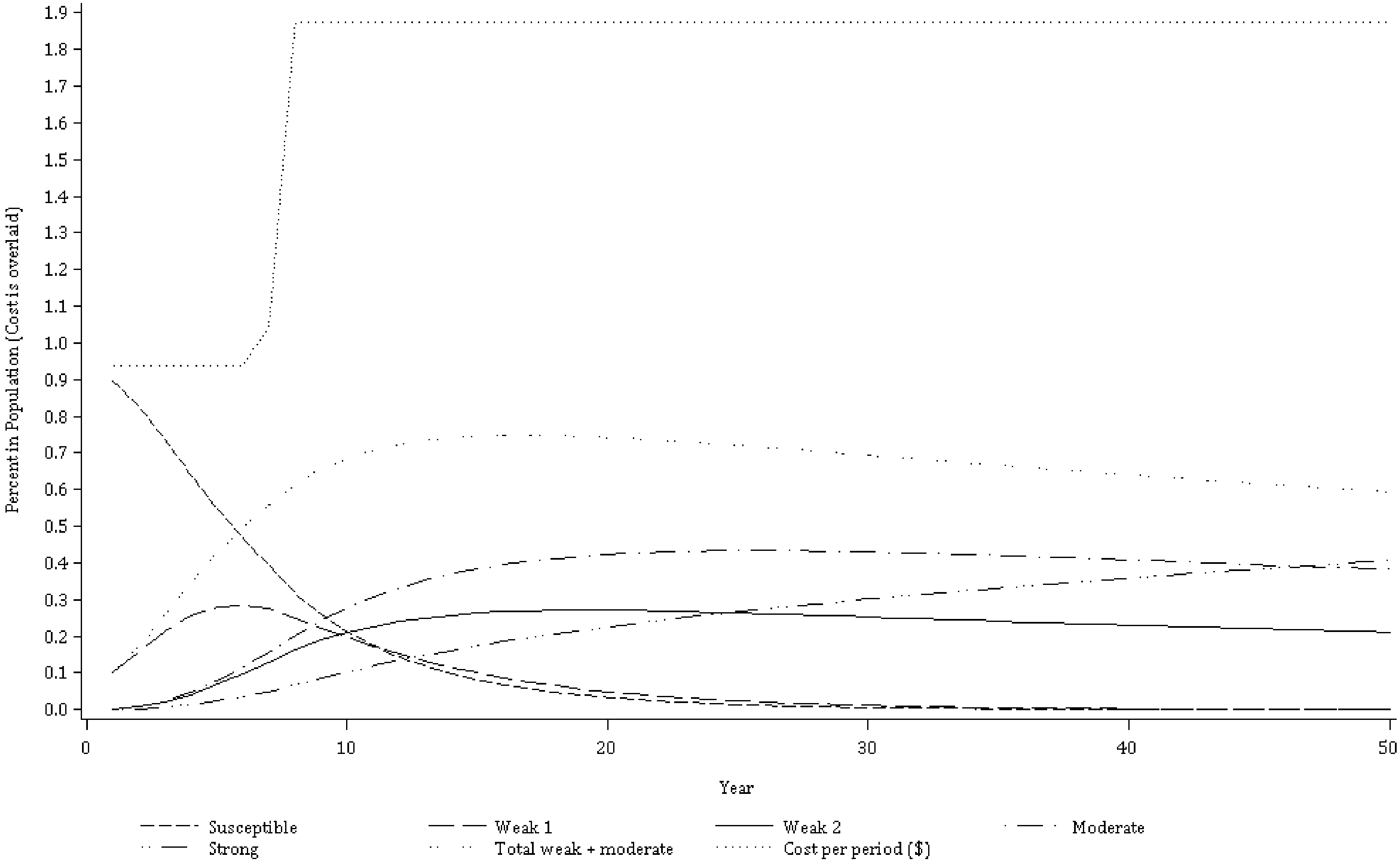

Figure 3. Period Cost/Tonne & Resistance Development for Calendar Based Fumigation (Fum. Effect. = 0.7, Emigrate = 0.05)

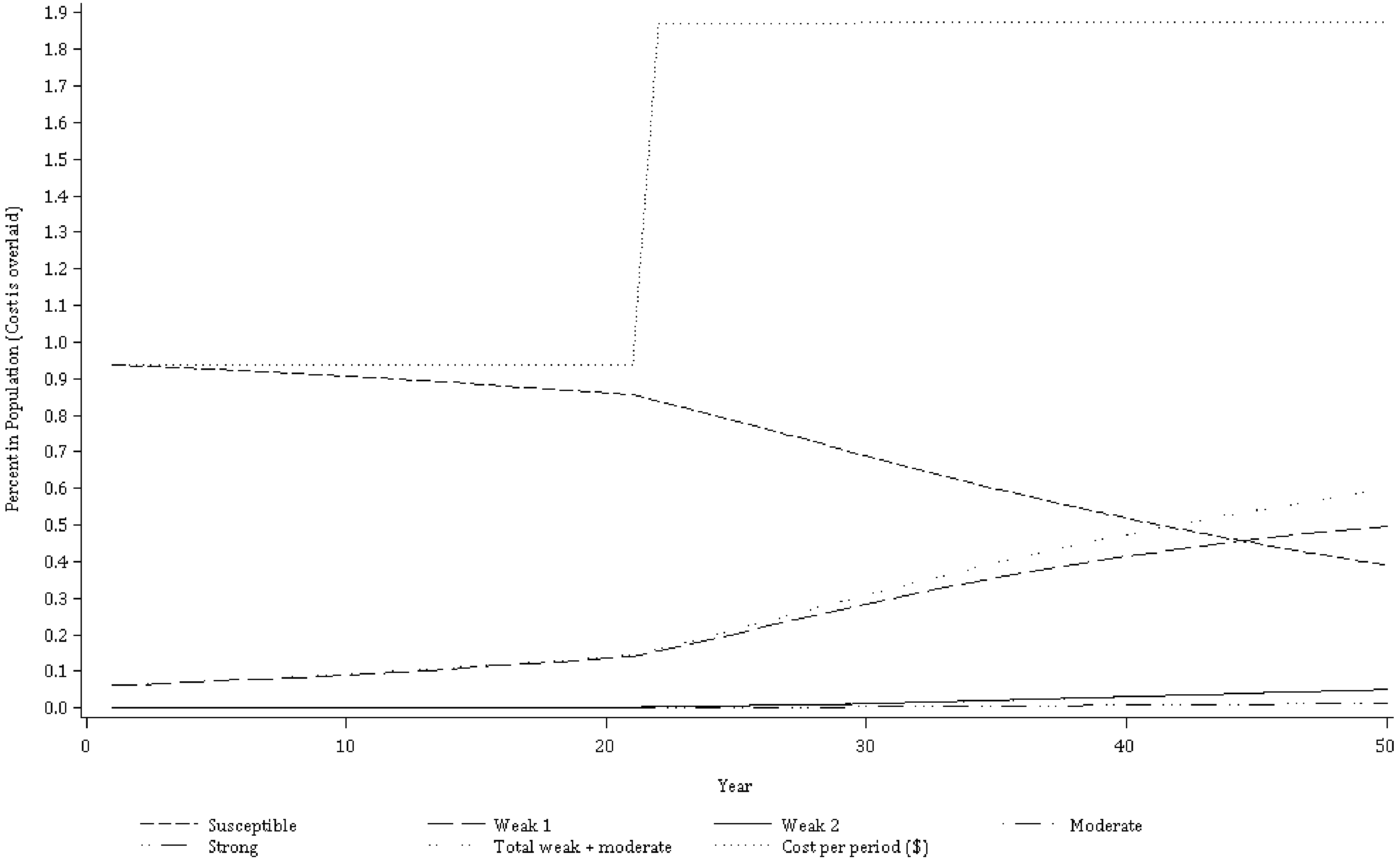

Figure 4. Period Cost/Tonne & Resistance Development for Calendar Based Fumigation (Fum. Effect. = 0.7, Emigrate = 0.4)

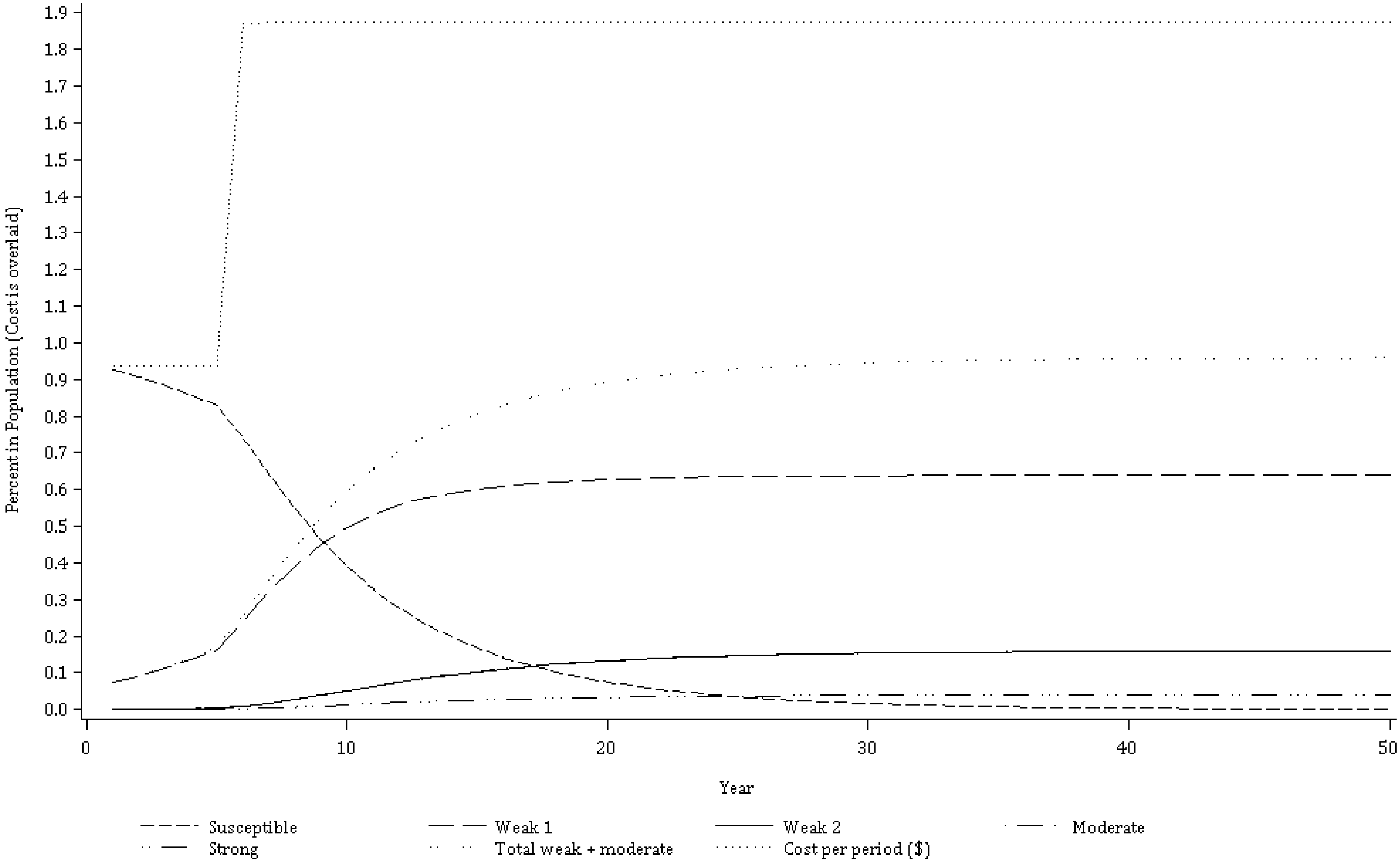

Figure 5. Period Cost/Tonne & Resistance Development for IPM (Fum. Freq. = 0.5, Fum. Effect. = 0.95, Emigrate = 0.05)

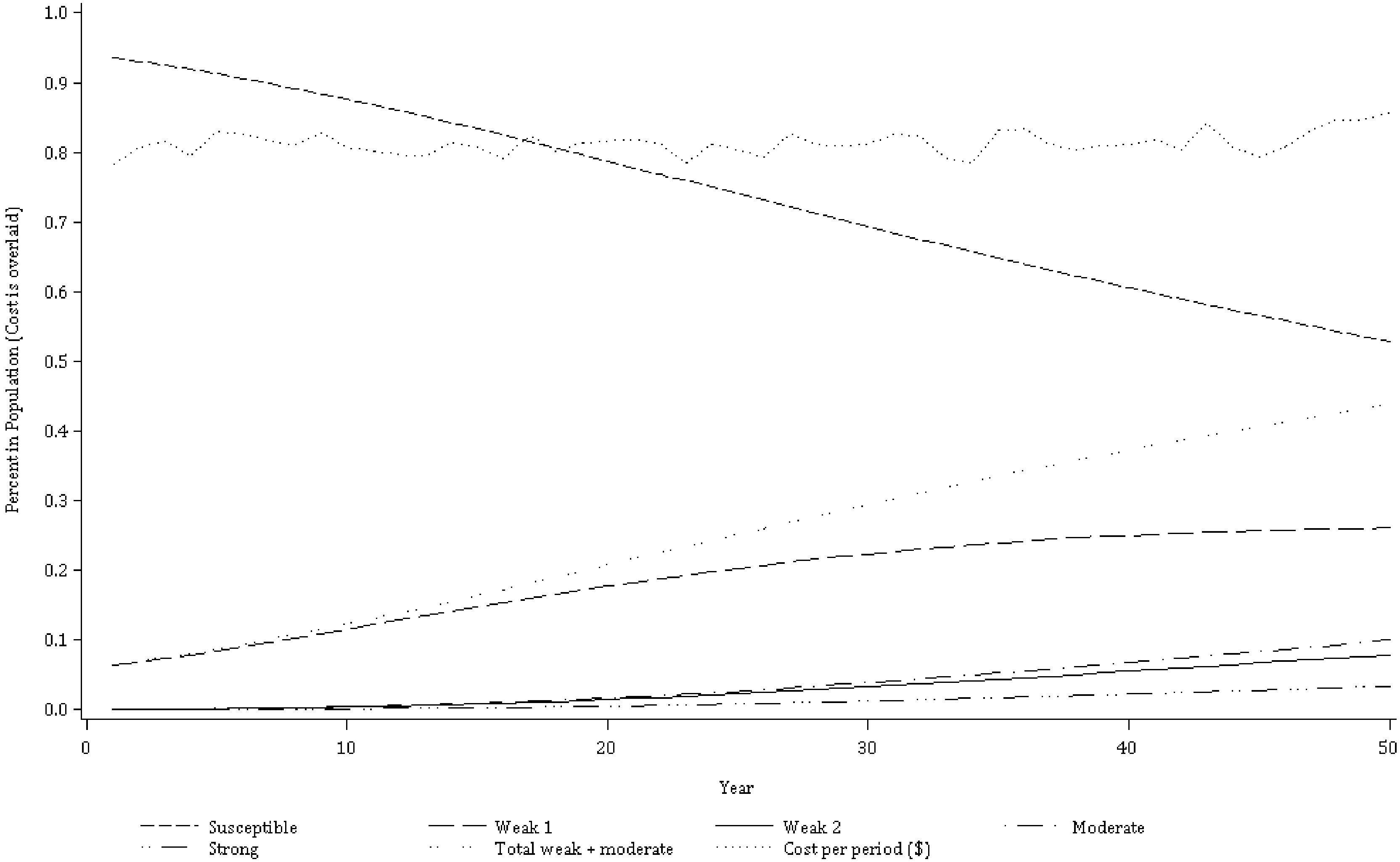

Figure 6. Period Cost/Tonne & Resistance Development for IPM (Fum. Freq. = 0.5, Fum. Effect. = 0.95, Emigrate = 0.4)

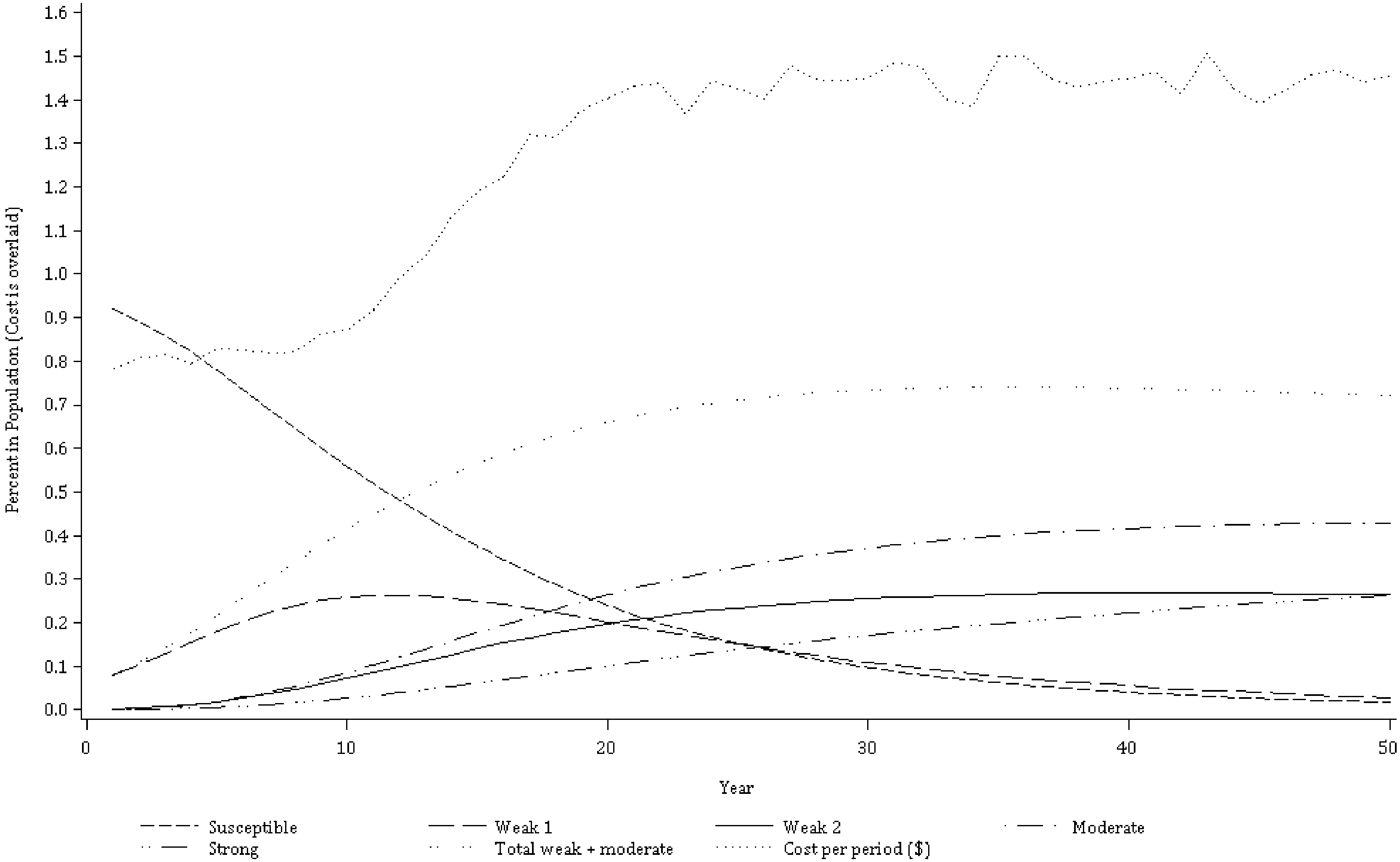

Figure 7. Period Cost/Tonne & Resistance Development for IPM (Fum. Freq. = 0.5, Fum. Effect. = 0.7, Emigrate = 0.05)

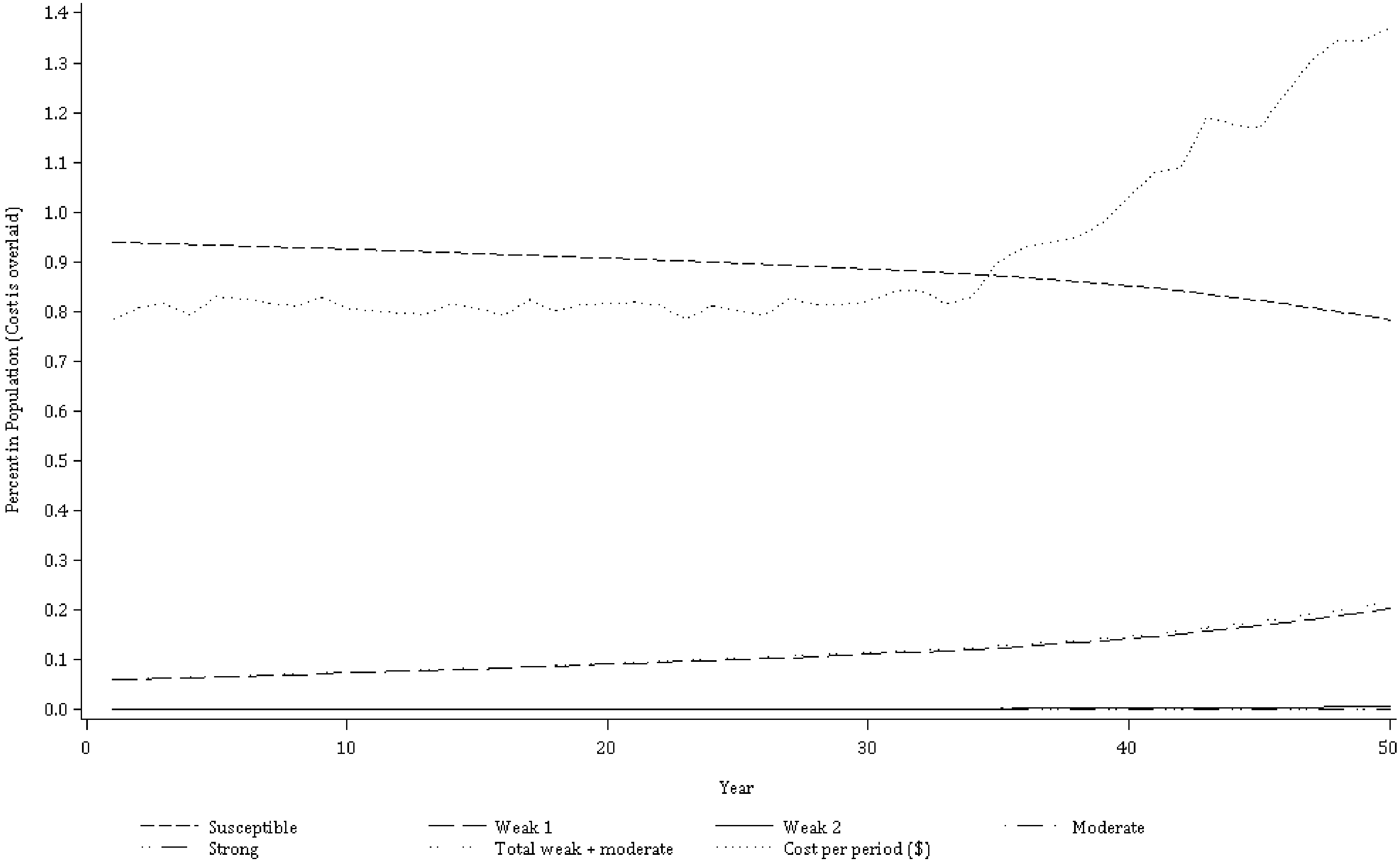

Figure 8. Period Cost/Tonne & Resistance Development for IPM (Fum. Freq. = 0.5, Fum. Effect. = 0.7, Emigrate = 0.4)