WPTC 04-08

International Agricultural Trade and Policy Center

ECONOMIC IMPACTS OF PINK HIBISCUS MEALYBUG IN FLORIDA AND THE UNITED STATES

By

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WPTC 04-08 **December 2004**

WORKING PAPER SERIES

UNIVERSITY OF FLORIDA

Institute of Food and Agricultural Sciences

INTERNATIONAL AGRICULTURAL TRADE AND POLICY CENTER

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Economic Impacts of Pink Hibiscus Mealybug in Florida and the United States

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Abstract

This paper estimates the direct and indirect impacts of the Pink Hibiscus Mealybug infestation on the economies of Florida and the rest of the United States. The approach involves a Markov chain analysis wherein both short run and long run expected damages from infestation are calculated. Use is made of the CLIMEX model that predicts the potential pest-establishment regions in the US. While predictions based upon the CLIMEX model extend the scope of damages beyond Florida, the damages are dependent upon the rate of arrival and detection of species in those regions. Damages are significantly higher when a longer time horizon is considered. When nursery owners bear the full cost of quarantines in the form of loss of sales and treatment costs of infected plants, the cost-effectiveness of quarantines as a regulatory tool is diminished.

Presented at the Annual International Agricultural Trade and Policy Center Conference, December 7-8, 2004

[1] Dale Meyerdirk, at the USDA-APHIS, graciously provided data related to the biological aspects of the PHMB and information on the CLIMEX model predictions, besides making available several articles on PHMB and commenting on this draft. Richard Clark with the Dept. of Agriculture and Consumer Services (DOACS), Florida provide data related to the quarantines in various counties of Florida. Help is also acknowledged from several others including Divina Amalin at APHIS, Florida, and Ed Burns with the DOACS, Florida.

Introduction

Invasive species management requires active participation of policy makers at various levels. Monitoring at ports of entry for prevention, inspection and quarantining of infested areas, biological, chemical and physical control are some of the several management options available to the policy makers. However, the implementation of such options is often done on an ad hoc basis and without considering the possibility of their effectiveness in terms of costs, risk reduction or damage mitigation. One specific example is the use of quarantines in order to prevent further spread of pests from an already infested region. Quarantines are a useful means of preventing pest-spread, but their effectiveness is limited by the modes of transport of the pest, number of ports of entry for the pest and availability of alternative means to control the pest at lower costs. For instance, certain pests can be kept under control through the use of biological agents at a much lower cost than trying to prevent their spread through costly quarantines. However, the application of quarantines is often guided by tangential objectives such as stemming the decline in trade in an infested region caused by adverse reaction to pest outbreak.

One such pest that underscores the above point is the Pink Hibiscus Mealybug (PHM). PHM has already arrived in southern region of Florida (and some other territories of the US), but has been kept under control due to an early and efficient use of biological control agents. However, it has not been eliminated and will continue to be considered a secondary pest under biological control, with new cases occurring every now and then[1]. As a consequence, policymakers have to invest significant resources towards minimizing their spread through monitoring and control. Private resource owners too incur substantial costs due to imposition of quarantines and mandatory treatments of infested plants. Considerable threat exists that the PHM will spread in to the rest of the US, thus increasing overall costs significantly. The overall annual cost of control and damages to the US economy from PHM have been estimated to be US $700 million, with the global total being about $5 billion (Mofitt 1999, ARS 2003). One study puts the economic costs of PHM invasion to US agriculture alone at $750 million/year when no control measures are taken (Mofitt 1998). PHM infestation outside the US has caused high agricultural losses. The agricultural losses to Grenada and Trinidad (in absence of control measures) in the first year of introduction of PHM have been estimated to be US $10 and $18 million respectively. Current economic losses exceed US $3.5 million per year in Grenada and US $125 million per year in Trinidad and Tobago (USDA-APHIS 2003). Whereas, in Puerto Rico this species was detected early on and biological control measures were employed, thus avoiding any agricultural losses (Michaud, 2002).

This paper estimates the current and potential costs of PHM infestation and spread to the economies of Florida and United States. These estimates, however, are based under the assumption that the regulator follows an 'optimum' policy of imposing quarantines in detected regions and releases biological control agents at all PHM infestation sites. A Markov chain framework is developed that incorporates the uncertainties associated with the biological (such as arrival and spread of species) and policy parameters (such as detection of infested regions) in order to calculate the expected economic damages, both in the long and the short run. Use is made of CLIMEX model predictions of the potential regions in the US favorable to this insect's establishment. Finally, Numerical simulations are performed and key policy issues are taken up in light of their findings.

This study would contribute to the literature on invasive species in several regards. First of all, the case of PHM is unique as it has hosts spanning more than 250 species, a large number of which are agricultural commodities of significant economic value. Findings from this study could be directly applicable to other invasive species affecting similar hosts in future. Second, the PHM has been detected only in parts of Florida and California, and is yet to spread into the rest of the United States. As a consequence, significant effort is being dedicated towards containing further spread of PHM through quarantine measures. By comparing the effectiveness of quarantine measures on rates of spread of PHM to the costs of such measures, this study lays out scenarios under which such policy measures could be justified. An indiscriminate policy of quarantining every infestation may provide perverse incentives to affected businesses and reduce its effectiveness by inducing under-reporting of infestations. Finally, this study also points out the long run implications of pest infestations by considering all possible scenarios of spatial infestation. Use is made of scientific predictions for ascertaining scenarios.

Biological Background

The PHM (native of India), first reported in Egypt in 1920, was introduced to the island of Grenada in the Caribbean in 1993. It has currently spread to 27 Caribbean islands. Its primary host is the *Hibiscus spp*. on which it rapidly grows into colonies and is believed to inject a plant-toxin causing severe distortions to the plant parts. Overall, it can affect more than 250 species of plants which include coffee, guava, citrus, grape, peanuts, rose, beans, coconuts, maize, sugar cane, soybean, cotton, etc. It is also found in regions of Africa, Middle East, India, Pakistan, and South East Asia (USDA and APHIS 2003). In the past it has led to a loss of up to 100% of agricultural output (grapes, jute, sorrel, etc.) in India. It is also found in Hawaii, but its effect has been minimal there due to the presence of its natural enemies.

Both sexes of the species are about 3 mm long. The average life cycle spans 45 days depending upon the temperature. A female can lay more than 500 eggs at one time. Identification of the bug is not easy and can be positively done only by a taxonomist. Modes of transport include crawler and egg sack dispersion through wind and by movement attaching or sticking to animals or transported objects. Nursery plants and trade of infested commodities also lead to its spread. Sometimes, ants that are attracted to its honeydew may act as protectors and movers of PHM.

A number of biological control measures such as parasitoids have been employed to control this invasive species with high success rates. Parasitoids grow inside the body of PHM and eat it internally, eventually leading to its death. One particular parasite, *Anagyrus kamali,* has been found to be very effective against the PHM. A generalist predator, the red headed ladybird beetle, *Cryptolaemus Montrouzieri* has been shown to be effective in controlling the PHM. A single ladybird beetle can kill about 3000-5000 Mealybugs in its lifetime. However, these may interfere with other biological methods like *Anagyrus kamali* by sucking on the parasitized PHM. While ladybird is considered a short-term solution to the PHM, parasitoids are the long-term solutions (USDA and APHIS 2003).

The biological parameters of the PHM and *A. Akamali* are compared in Table 1. Figure 1 shows the time paths of PHM and *A. kamali*. Notice that *A. kamali* takes over the PHM population within a short span of 10 days even though its starting population is one tenth of the PHM's starting population.

INSERT TABLE 1 and FIGURE 1 HERE

Though the biological control methods have been found to be very effective, they will not lead to eradication of the PHM. As a consequence, biological methods may need to be combined with other measures to ensure maximum safety. Most pesticides have been found to be ineffective due to wax like secretion on the PHM's body, which cannot be easily penetrated (USDA and APHIS 2003). However, Zettler et al. (2002) find that post harvest treatment of PHM-affected crops with Methyl bromide leads to 100% mortality of the PHM at all stages. Methyl bromide may adversely affect the quality of the treated crop and as a result is used selectively on certain crops.

The PHM does not directly harm humans. The biological agents too have been argued to be harmless. There has been no non-target impacts of the parasitoids used against PHM to date.

Economic Issues

This paper models the economic impacts of PHM infestation by incorporating the damages from pest infestation together with the costs of management options, such as quarantines, into a stochastic framework that considers the risks of pest infestation and spread. The paper, however, does not seek to optimize with respect to the costs and benefits of PHM management. Instead, it takes the current management strategies as given and considers the long term implications of such strategies on PHM spread and subsequently on the economy. This approach is influenced by two main considerations. First, the management options are currently limited to control measures due to the fact that PHM has already arrived in Florida and some other parts of the US. Second, biological measures of control are highly effective, but they cannot fully eliminate the pest. As a consequence, quarantine measures are being combined with biological measures to prevent its further spread. Current management strategy allows for limited variability in the use of either biological methods or quarantines. Therefore, the key issue is to consider the cost-effectiveness of such measures as the pest spreads. A stochastic analysis of the pest spread and its damages (influenced by control measures) would help guide PHM management in the long run.

The economic impacts of PHM can be classified into direct and indirect. Direct impacts include the costs of prevention, control and monitoring besides the damages to the host species. The indirect impacts include loss in businesses from quarantine, loss in trade from supply disruptions and non-tariff barriers to prevent the arrival and spread of the pest. Most studies on economic impact of invasive species fail to adequately incorporate these indirect impacts, which could overwhelm the direct impacts. In this paper the indirect impact from quarantines is considered explicitly as a part of the overall damages from PHM.

Tables 2 through 6 below calculate the direct annual economic losses from PHM infestation. The estimation procedure is based upon an earlier work by Moffitt (1999) where the economic losses to key agricultural hosts of the PHM were calculated based upon expert predictions of the damages to hosts in the event of no control being taken. Using the same estimates of the proportional losses to hosts such as Avocadoes, Cotton, Citrus, Soybean, vegetables, peanuts and Nurseries, economic losses are recalculated. While these estimates give a rough account of potential damages caused by the PHM, a much more detailed analysis is required to understand the threat from this pest both in terms of its spread probabilities using scientific information and incorporating the indirect economic losses.

INSERT Tables 2-6 HERE

In order to make more scientifically informed calculation of the potential damages from the pest we make use of the CLIMEX model predictions of the degree of infestation of PHM in the United Sates. The CLIMEX model was developed by the Commonwealth Scientific and Industrial Research Organization and Cooperative Research Center for Tropical Pest Management, Australia. This model uses PHM-infested regions in the world that resemble the climates at various locations in North America to predict the possible establishment of the PHM. Two predictions are available based upon 'match levels' of 0.5 and 0.6. The match levels are based upon the climatic similarity of locations under study in the CLIMEX model to the regions in North America (USDA-APHIS 1998). A match level of 1 would imply that the climate of the target location matches perfectly with the climate of the region where the infestation has taken place in the past. Based on this ranking, a point 0.6 match level can be understood to have a higher predictive capacity. At 0.6 match level, eleven sensitive States in the US were identified as potential locations for PHM infestation. These are: Alabama, Arizona, California, Florida, Georgia, Louisiana, Mississippi, New Mexico, North Carolina, South Carolina, and Texas. At 0.5 match level potential States are: Alabama, Arizona, California, Florida, Georgia, Arkansas, Louisiana, Maryland, Mississippi, Nevada, New Mexico, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia.

Using a 0.6 match level, economic losses are estimated and presented in Tables 2 through 6 above. Notice that there is a significant reduction in predicted damages after using CLIMEX model forecasts.

Next we model the indirect impact of PHM infestation such as loss in business from quarantines, treatment costs etc. We model the total economic impact of PHM through a Markov chain analysis. Since the pest is under control in the Florida region, the direct economic damages are minimal. However, there has been a continuous arrival of new pests in the various counties over the last three years. Figure 2 shows the arrival sequence into various counties of Florida.

INSERT FIGURE 2 HERE

Due to these constant arrivals, regulatory agencies such as the USDA enforce quarantines on the infected regions. These quarantines are mostly imposed upon nurseries, as Hibiscus (a nursery plant) being the primary host of this insect is the first one to be infected. There is a significant cost to the nurseries from loss of revenues during the quarantined period besides the costs of treating infested areas. Several nurseries have gone out of business due to such quarantines in the past years[2]. Figure 3 shows the composition of Nurseries in terms of their annual revenues. Yet, the significance of such quarantines cannot be overemphasized in terms of reduction in risk of spread outside Florida into the rest of the US.

INSERT FIGURE 3 HERE

The approach adopted in this paper is to model the processes in the PHM infestation (such as arrival, spread, re-infestation, etc.) and regulatory reactions (such as quarantines) as a continuous time Markov process. A continuous time Markov process assumes that the rates (of arrival, spread, detection, etc. of pests) follow an exponential distribution. That is, a process shifts from one state of the system into another after an exponential amount of time. Such processes have been commonly used to describe biological phenomenon such as the birth and death rates of species. Parameters related to pest infestation have been modeled as emanating from a Markov process in the past (Zimmerman 2002). Markov chains have also been highly successful in mimicking various societal phenomenon such as labor migration, population distribution, traffic movements etc. One major advantage of such an approach is that it offers convenience of empirical estimation and transparency of analysis.

Model

The model below delineates the US region into two parts, FL named as region A and rest of US, named as region B. There are three main 'states' possible for these regions, namely; un-infested (*u*), infested (*i*) and under quarantine (*q*). Given these three main 'states', the possible state space is a nine by one matrix as shown below:

$$\{A_u B_u, A_u B_i, A_u B_q, A_i B_u, A_i B_i, A_i B_q, A_q B_u, A_q B_i, A_q B_q\}$$

These states capture the various possible combinations that are possible between the two regions[3]. For instance, $A_u B_u$ refers to the state when both the regions are free of any infestation and $A_q B_u$ refers to the state when Florida is in the state of quarantine and rest of the world is un-infested[4].

Key Parameters[5]:

The important parameters of concern are the arrival rates of PHM from an outside region into Florida and the rest of US (a_e, b_e), the rates of infestations from one region into another (a_i, b_i), rates of detection of an infestation (d_a, d_b), rates of disinfestations of infested regions due to control measures(δ_a, δ_b), rates of disinfestations of quarantined regions (δ_{aq}, δ_{bq}), and the rates of re-infestation of the quarantined regions (r_a, r_b). All rates are defined in terms of units per year and are detailed below:

Arrival rate into regions B and A (b_e , a_e) : The arrival rates are defined as the number of arrivals of the pest per unit of time. In certain cases it may not be possible to measure the exact stock of pests that arrive at the point of interest or relate that stock meaningfully to economic damages. An alternative measure in such cases would be to relate the arrival rate to certain observable parameters such as number of observations of pest infestation over a certain period.

Infestation rate from A to B and from B to A (a_i, b_i): Infestation rates between two regions are defined as the number of transmissions of pest from one infected region to another within a certain time period. For practical purposes, these transmissions could be measured by the number of detections of infested shipments from one region to another.

Rate of disinfestations from a region due to bio-control (δ_a, δ_b): Rate of dis-infestation is defined as the time it takes for pest to be eradicated from a certain region. Alternatively, it could also be measured as the number of disinfestations per unit of time.

Rate of dis-infestation after quarantine (δ_{aq}, δ_{qb})*:* It is possible for the quarantined regions to be dis-infested at a different rate as compared to infested regions that are not yet quarantined.

Rate of re-infestation of a quarantined region (r_a, r_b)*:* This parameter incorporates the possibility that quarantined regions may fall back into a state of infestation instead of getting dis-infested after the quarantine is removed.

Rate of detection of infested regions and fall into quarantined states (d_a, d_b): This measures the rate at which infested regions are detected and placed under quarantine.

These rates define the transition process from one state of the system into another. For instance, when the arrival rate of species into Florida is higher than that into the rest of the US, the likelihood of finding states when Florida is infested as compared to those when the rest of the world is infested would be higher over a given time horizon. Given such rates, it is also possible to find the long term behavior of the system, which is of special interest to us as it would throw light on the economic aspects of pest infestation in the long run. The transition diagram is shown in the figure below.

INSERT FIGURE 4 HERE

Rate Equations

In order to solve for the long-term behavior of the system, one needs to look into the steady state behavior of the system. The steady state is derived from the fact that in the long term, the net arrival out of any given state must equal the net entry into it. Using this, we derive the first nine of the below equations. In these equations, P (with subscripts) represents the long-term probability of finding the system in that state. This term can also be interpreted as the fraction of time spent in that state in the long run. The last equation (10) is derived from the fact that the sum of the fractions of time spent in all possible states must equal one.

(1) $P_{uu}(b_e + a_e) = P_{ui}\delta_b + P_{iu}\delta_a + P_{qu}\delta_{aq} + P_{uq}\delta_{bq}$

(2) $P_{ui}(d_b + b_i + a_e + \delta_b) = P_{uq}r_b + P_{uu}b_e + P_{ii}\delta_a + P_{qi}\delta_{aq}$

(3) $P_{uq}(r_b + a_e + b_i + \delta_{bq}) = P_{ui}d_b + P_{iq}\delta_a + P_{qq}\delta_{aq}$

(4) $P_{iu}(a_i + b_e + d_a + \delta_a) = P_{ii}\delta_b + P_{qu}r_a + P_{uu}a_e + P_{iq}\delta_{bq}$

(5) $P_{ii}(d_b + d_a + \delta_b + \delta_a) = P_{iu}(a_i + b_e) + P_{ui}(b_i + a_e) + P_{iq}r_b + P_{qi}r_a$

(6) $P_{iq}(r_b + d_a + \delta_a + \delta_{bq}) = P_{ii}d_b + P_{uq}(a_e + b_i) + P_{qq}r_a$

(7) $P_{qu}(r_a + a_i + b_e + \delta_{aq}) = P_{iu}d_a + P_{qi}\delta_b + P_{qq}\delta_{bq}$

(8) $P_{qi}(\delta_b + r_a + d_b + \delta_{aq}) = P_{qu}(a_i + b_e) + P_{ii}d_a + P_{qq}r_b$

(9) $P_{qq}(r_a + r_b + \delta_{bq} + \delta_{aq}) = P_{qi}d_b + P_{iq}d_a$

(10) $P_{uu} + P_{ui} + P_{uq} + P_{iu} + P_{ii} + P_{iq} + P_{qu} + P_{qi} + P_{qq} = 1$

Solution of these rate equations would yield the steady state probabilities *P*. Once the fraction of time spent in each state is derived, the economic analysis is fairly straightforward. For instance, if one is interested in solving for the expected damages in the long run, given the above characteristics of the system, the analysis would involve multiplying the economic damages in each of the states by the fraction of time spent in each state as:

(11) $$\sum_{x}^{y} D(P_{xy}) * P_{xy}$$

Damages under Time Discounting

The above presented a way to calculate the expected sum of damages from various possible states of PHM infestation over a year. However, one key question of concern may also be the expected sum of damages over a longer period of time when the planner may have time preferences. It is pertinent to note that when the expected damages are taken over a longer time horizon, the current state of infestation may have an influence over the total sum. That is, the sum of expected damages would vary depending upon whether one started in $A_u B_u$ or $A_q B_q$. This is because, each state of the system has a unique steady state rate of departure and entry that may be different from the others. In order to calculate an infinite horizon sum of damages, we define *g*(*x*,*y*) as the sum of damages if one started in state *x* for Florida and state *y* for the rest of the US. Following the derivation of average expected discounted costs in Kulkarni (1995), the relation between the generator matrix (*Q*), per period payoffs in each state and the long run expected profits from starting in each state can be derived as follows [7]:

$$(12) \qquad \left[\rho I - Q\right] \begin{bmatrix} g_{uu} \\ g_{ui} \\ g_{uq} \\ g_{iu} \\ g_{ii} \\ g_{iq} \\ g_{qu} \\ g_{qi} \\ g_{qq} \end{bmatrix} = \begin{bmatrix} D(P_{uu}) \\ D(P_{ui}) \\ D(P_{uq}) \\ D(P_{iu}) \\ D(P_{ii}) \\ D(P_{iq}) \\ D(P_{qu}) \\ D(P_{qi}) \\ D(P_{qq}) \end{bmatrix}$$

The generator matrix Q, which is basically Figure 4 in the matrix form is derived below. The right hand side denotes the per-period damages in each state.

INSERT FIGURE 5 HERE

Note that the diagonal elements, which are marked with stars, represent the negative sum of all rates in that row. For instance, the first row represents the departure rate out of the state $A_u B_u$ into all other states. The elements of column one and row one seek to balance the departure rate out of this state.

Empirical Estimation

Estimation of the key parameters of the model (such as the arrival and spread rates of the PHM) is no mean task even for a simple model like this. There has been little scientific work done to get estimates of the arrival and infestation rates of this species. Most of the work is currently focused upon surveying the impact of biological control agents on the PHM. There have been some observations of PHM behavior under simulated conditions in the laboratory that have yielded the growth and survival rate for PHM and its biological control agents such as *A. Kamali*. However, at this stage there is limited information available with respect to the specific interaction between the PHM and its innumerous hosts. For a more detailed modeling approach, one would require information such as the density of PHM species on each host plant and the variance of this density in presence of multiple hosts. As a consequence, our estimates of the various rates are based upon some simplifying assumptions. The arrival rates, rates of detection and quarantine, re-infestation and disinfestations rates are all calculated from data available on quarantine of nurseries in the ten counties of Florida so far. Since the infestation has not spread beyond Florida, hypothetical estimates of the same rates are proposed. Below is presented a brief account of derivation of these rates.

The arrival rate into Florida is based upon the assumption that the number of detections in various counties of Florida was each independent arrival from an outside region. Further assuming that the arrival rate was a Poisson process, the average arrival rate into Florida (a_e) was estimated to be 12.33 per year. Since there have been no known infestations into regions outside Florida (except California and Hawaii), we assume a very low arrival rate from outside into the rest of the US (b_e=.001). Ideally, infestation should be defined in terms of the pest reaching some critical observable threshold. However, practically, infestations are recognized only after detection on some private property or in nurseries. Consequently, infestation and detection rates are treated as same in this paper.

Assuming that Florida is one of the first States to be infested, any further infestations into the rest of the US can be deduced from number of infestations outside the Florida region. Between 2002 and 2004, there has been only one detected case of a shipment of infected nursery plants outside Florida. Given one such case of arrival outside, one can assume the rate of infestation from Florida (region A) to the rest of the US (B) to be 1/3. However, since there are forty nine such States, the arrival rate into the rest of the US must be further divided by forty nine[8] ($a_i = \frac{1}{3*49}$). Due to no cases from the rest of US into FL yet, we assume the rate of infestation from B to A as very low (b_i =.001).

An important point to note here is that the PHM is under control in Florida due to the effectiveness of bio-control agents such as *A. Kamali* and others. However, there are two important clauses to this; first it takes roughly one year for a new infestation to be brought under 90-95 percent control (Amalin et al. 2003) and second, following the first, it is not possible to eliminate the bug. From the first fact we can deduce the rate of dis-infestation of the infected region to be 1(δ_a =1, δ_b =1). The second fact emphasizes that even dis-infested regions can fall back into a state of infestation.

A distinction needs to be made between disinfestations from states that are quarantined and from states that are infected. While most of the hosts of the bug are crops of significant agricultural value, the major host is the hibiscus plant, which is grown in nurseries. It is significant to note that all detections so far have been made in the nurseries, following which they were placed under quarantines. Quarantines, whereas they reduce the chances of further spread, they also impose significant economic hardships on the nurseries' revenues in terms of forgone sales, costs of treatment of infected plants and even closure of businesses. In Florida, there were 575 nursery-days of quarantines on 15 nurseries, whereas in 2003, there were 1008 days on 22 nurseries combined[9]. This gives the average time spent by a nursery in quarantine as 0.12 years per year. The rate of departure out of quarantine into dis-infestation is then given by the reciprocal of the average time spent in the state of quarantine. From this we derive: δ_{aq} =8.67 δ_{bq} =8.67.

It is also possible that there is an instantaneous re-infestation of quarantined regions after the quarantine is lifted. However, the data revealed a time lag before re-infestation of the previously quarantined regions. Consequently, we assign low possibilities to such events as: r_a =.001, r_b =.001. Finally, we assume that all infestations into nurseries are detected at the same rate as their arrival, giving us the average rate of fall into quarantined states as: d_a =12.33, d_b =(1/3*49).

Note that the above estimation of parameters is based upon observations at a disaggregated level of nurseries. It is possible that the rates of arrival, quarantine and infestations outside Florida may differ when the problem is considered at a much aggregate level of two regions. For instance, the rate of infestations outside of Florida may be expected to be higher when the entire State is infested as compared to the case when only a few counties are infested. Keeping such limitations in mind, we may consider the above estimation to be the base case scenario. Next, we derive the steady state fraction of time spent in each of the nine system-states as given below by the Pmatrix:

(13) $$\begin{Bmatrix} P_{uu}, P_{ui}, P_{uq} \\ P_{iu}, P_{ii}, P_{iq} \\ P_{qu}, p_{qi}, P_{qq} \end{Bmatrix} = \begin{Bmatrix} .307 & .0016 & 1.3X10^{-6} \\ .283 & .0015 & 1.2X10^{-6} \\ .403 & .0023 & 1.8X10^{-6} \end{Bmatrix}$$

It is evident from above that the chances of infestation into the rest of the US are fairly insignificant in the base case scenario. This is affected by our assumption of low infestations out of Florida and from outside regions into the rest of the US. Also, the system spends most time in the states when Florida is either un-infested, infested or quarantined. These assumptions will have an impact on total expected damages accordingly. Next, using the figures in Tables 2 though 6, we calculate the damages from these various states, defined as the Dmatrix (in million US $)[10]:

$$\begin{bmatrix} D_{uu} = 0 \\ D_{ui} = 1{,}418.140 \\ D_{ui} = 1{,}418.140 \\ D_{uq} = 4{,}374.894 * 2 \\ D_{iu} = 162.856 \\ D_{ii} = 162.856 + 1{,}418.140 \\ D_{iq} = 162.856 + 4{,}374.894 * 2 \\ D_{qu} = 1{,}006.649 * 2 \\ D_{qi} = 1{,}006.649 * 2 + 1{,}418.140 \\ D_{qq} = 4{,}374.894 * 2 + 1{,}006.649 * 2 \end{bmatrix}$$

Note that while solving for the damages in the quarantine stages we multiply the loss to businesses from quarantines by a factor of two in order to incorporate some of the treatment costs. A brief telephonic survey revealed that nursery owners spent almost as much as their monthly revenues over the treatment costs. Societal treatment costs, such as release of parasitoids are much higher, however such costs are assumed to be adequately covered in this doubling of the quarantined costs.

The expected sum of damages to the entire US region in one year is, simply, the sum of the product of elements in the Pmatrix with the corresponding elements in the Dmatrix and equals US $871.787 million. Note that this figure is significantly lower than the average annual damages of US $1,581 million as calculated earlier (as shown in Table 6). This is due to the fact that the Markov model assigns lower steady state risks to the rest of the US being in either the infested or quarantines states. Whereas, the earlier estimate does not incorporate the risk-aspect of the PHM problem. In order to calculate the expected discounted sum of damages over an infinite time horizon, we solve the gmatrix for various states. The matrix of g's is derived for ten, five and one percent interest rates respectively as (million US$):

$$\begin{bmatrix} g_{uu} \\ g_{ui} \\ g_{uq} \\ g_{iu} \\ g_{ii} \\ g_{iq} \\ g_{qu} \\ g_{qi} \\ g_{qq} \end{bmatrix} = \begin{Bmatrix} 8,637 \\ 9,918 \\ 9,634 \\ 8,707 \\ 9,988 \\ 9,704 \\ 8,770 \\ 10,050 \\ 9,766 \end{Bmatrix} \begin{Bmatrix} 1,7350 \\ 1,8700 \\ 1,8360 \\ 1,7420 \\ 1,8770 \\ 1,8430 \\ 1,7490 \\ 1,8830 \\ 1,8490 \end{Bmatrix} \begin{Bmatrix} 8,7100 \\ 8,8500 \\ 8,8100 \\ 8,7170 \\ 8,8560 \\ 8,8170 \\ 8,7230 \\ 8,8620 \\ 8,8240 \end{Bmatrix}$$

$$(10\,percent) \qquad (5\,percent) \qquad (1\,percent)$$

First thing to note here is that the long run damages are considerably higher than the annual estimates . Further note that the damages increase as the discount rate is lowered from 10 percent to 1 percent. Also note that for a given discount rate, the highest damages are felt when the system starts with quarantine in Florida and infestation in the rest of the US. The least damages occur when the current state is of un-infestation in both the regions, which is obvious. The states of quarantine cause high amounts of damages, a result of incorporating the indirect economic impacts of the pest. Important insights emerge from presenting the discounted sum of damages based upon the starting state of the system. For instance, consider the results for the ten percent discount rate. When the starting state is that of un-infestation in Florida, damages are higher with the rest of the US being in the state of infestation as compared to it being in the state of quarantine (compare g_{ui} & g_{uq}). Whereas, when the starting state is that of un-infestation in the rest of the US, damages are higher when Florida is in the state of quarantine as compared to it being in the sate of infestation (compare g_{iu} & g_{qu}). This anomaly, is primarily due the long run propensity of the system to spend a high fraction of time in the state where Florida is quarantined and the rest of the US is un-infested. This has important policy implications as it warns against complacency. The fact that the system is currently free from infestation is no indicator of the extent of damages in future. It is possible that certain states may take a speedier transition to the most damaging states as compared to others. The long run spatial distribution of pests is an important piece of information to strive for, and management decisions based solely upon current state of the system could be misleading. Therefore, besides understanding the magnitude of resources at risk, it is also important to relate them to the long run risks in the chain of events.

Expected Damages based on the CLIMEX model Predictions

Using the 0.6 level predictions for potential establishment regions in the US we derive the damage matrix as (million US$):

$$\text{Damage Matrix} = \begin{bmatrix} D_{uu} = 0, \\ D_{ui} = 675.047 \\ D_{uq} = 3883, \\ D_{iu} = 162.856 \\ D_{ii} = 837.903 \\ D_{iq} = 4{,}045.8 \\ D_{qu} = 2{,}013.3 \\ D_{qi} = 2{,}688.34 \\ D_{qq} = 5{,}896.29 \end{bmatrix}$$

Taking the sum of product of the elements in damage matrix with the probability matrix as above we get the expected sum of damages per period in the steady state as US $867.580 million. Note that these damages are almost equal to the ones estimated above. This is primarily due to our assumption of the system spending very little time in states when the rest of the US is either infested or quarantined. As a consequence, the damages captured here are still those in the Florida region. Finally, the total discounted value of expected damages over an infinite time horizon for a 10 percent discount rate horizon is derived as (million US$):

$$\begin{bmatrix} g_{uu} \\ g_{ui} \\ g_{uq} \\ g_{iu} \\ g_{ii} \\ g_{iq} \\ g_{qu} \\ g_{qi} \\ g_{qq} \end{bmatrix} = \begin{Bmatrix} 8{,}599 \\ 9{,}209 \\ 9{,}041 \\ 8{,}669 \\ 9{,}278 \\ 9{,}111 \\ 8{,}731 \\ 9{,}340 \\ 9{,}173 \end{Bmatrix}$$

Opportunity Cost of Quarantines

As is evident from the steady state matrix of transition probabilities derived above, the system spends most of the time in the state when Florida is quarantined. One crucial issue is whether the costs of quarantine are worth their utility. We do not really know what kind of infestation rate we would get into the rest of the US if the quarantines were not imposed into Florida nurseries. Assume that the current rate of infestation from

Florida into the rest of the world a_i=1/(3*49) is a result of the stringent quarantine efforts. Also assume that in the absence of quarantines the rate of arrival into Florida will equal the rate of departure out of Florida and into the rest of the US (a_i=12.33). In such a case the annual impact to the overall economy of the US when no quarantines are imposed, can be derived by taking a product of the revised damage matrix with its long run steady state probabilities. Note that the revised damage matrix would have zero damages in the states of quarantines for either of the regions. Following the above approach, the expected annual damages are derived to be US $205.697 million. The impact on the US economy in the presence of quarantines is the base case scenario derived above as US $867.580 million. Therefore, taking the difference between the two we find that the opportunity cost of quarantines is actually a positive number equal to US $661.883 million. This extra cost of quarantines can only be justified if either the damages are expected to be much higher than assumed above or if the risks of spread are greater. However, the actual cost of quarantines may itself be lower if businesses do not suffer complete loss of sales during the quarantine period as assumed here, or if the treatment costs which are included as a part of quarantines are much lower. In the above simulations it was assumed that the treatment costs of infected plants in the nurseries were equal to the loss of sales, thus doubling the quarantine costs. In the following section we relax some of the above assumptions to gain further insights.

Sensitivity Analysis and Conclusion

Using the above CLIMEX predictions as the base case we perform some simulations to study the impact of variations in our assumptions over the key parameters. The results of these simulations are presented in Table 7 below.

INSERT Table 7 HERE

Case 1 looks at a case when the rest of the US, as predicted by the CLIMEX model, have the same escape rate as the arrival rate into Florida. Further, the rate of detection in the rest of the US remains as before. That is, $a_i = 12.33$, $d_b = 1/(3*49)$. Damages increase significantly after this manipulation. However, when the rate of detection is increased to a high level, equal to the rate of arrival, (case 4), the damages are almost three times higher as compared to the base case. Notice that quarantines have a large impact on the damages and therefore must be justified in terms of their impact on future risk reduction. With increasing susceptibility of the geographical region, either due to trade or exogenous reasons, the arrival and spread rate of species may not show any linear relationship to quarantines beyond a certain threshold. That is, beyond a certain point the effectiveness of quarantines fall whereas their costs may rise. Therefore, it is significant to know the relation between the impact of quarantines on future risk of pest spread and consequential damages in order to justify their costs. Case 2 leads to lower damages than the base case as the control measures are twice as effective leading to higher rates of disinfestations. Damages are twice as high as the base case when the arrival rate into the rest of the US from outside is increased significantly. Finally, when the costs of quarantine are reduced to half, by restricting to loss in revenues only, the expected damages are reduced to half their value from the base case. However, this number is still twice as much as the case when quarantines are not imposed at all, as shown above in the calculation of the opportunity cost of quarantines.

At this stage the paucity of data does not allow us to put our bets on any of these numbers derived above, but the simulation analyses do help throw light on the merits of regulatory policies such as quarantines. It is evident that that there is a limit to which such measures can be effective. Beyond a certain point when the arrival rate of species increases due to exogenous reasons, or when the costs of preventing arrivals increase, it would be wise to take recourse to alternative ways of pest management such as direct control. The main findings of the paper are not the high economic damages from PHM infestation, but the fact that high damages could itself be partly caused by the 'optimal' management procedures such as quarantining every case of detection, unless care is taken to consider the cost-effectiveness of such policies. It is also important to allocate policy measures based upon the long run impacts rather than a short-term horizon, as the damages from the pest are dependent upon the spatial distribution of pest in the long run.

Endnotes

[1] In 1999, it was found in the imperial county of California. In 2002, the PHM was located in Broward and Miami-Dade counties of Florida. By the end of 2004, more than 10 counties in Florida were reported to have PHM infestation.

[2] While regulators make an effort to restrict the impact of quarantines to the sale of the infested plant, the actual impact depends upon the severity of infestation and the number of host plants infested. Communication with the affected nurseries has revealed that this impact could range from partial to entire loss of revenues during the period of quarantines. In this study, it is assumed that quarantines lead to a total loss of revenues.

[3] The 'states' of the system should not be confused with the fifty 'States' in US.

[4] 'Florida being in a state of quarantine' is a figure of speech. It is possible that multiple states such as quarantine and infestation exist in the same region, and is a function of the level of dis-aggregation assumed within a region. For instance, if quarantines are placed solely on nurseries (which is the case now) it is possible to classify the states as has been done in the paper. When quarantines are placed also on the agricultural sector, the state space would have to be enlarged and states redefined.

[5]The estimation of the key parameters was based upon past data on quarantines on infested nurseries in Florida. This data was provided by the Florida department of Agriculture and Consumer Services, and is available on request.

[6]There are two more arrows connecting states $A_q B_i$ to $A_u B_i$ and $A_u B_q$ to $A_u B_i$ that have been omitted in the above figure to maintain presentability.

[7]See Kulkarni (1995) pgs. 306-11 for more details

[8]At this stage there is no scientific information over the exact probability of arrival into each of the individual 50 States. The division by 49 is done under the belief that the 49 States face a uniform chance of receiving the infested material. Further, no distinction is made between arrival rate into Florida from outside and arrival from within due to infested shipments.

[9]These exclude quarantines imposed due to re-infestations.

[10]Note that we need to subtract the values of Fl from the US to arrive at a rest of the US figures.

References

1. Amalin, D. M. K. A. Bloem, D. Meyerdirk, and R. Nguyen. "Biological Control of Pink Hibiscus Mealybug in South Florida: A One Year Assessment", USDA-APHIS, Manuscript (2003).
2. ARS . "On the Lookout for Scaly Invaders" (2003): URL (http://www.ars.usda.gov/is/AR/archive/dec03/scaley1203.pdf)
3. Clark, R. A., DOACS, IFAS, University of Florida . List of Nurseries Quarantined under the Pink Hibiscus Control Program Since 2002, Personal Communication (2004).
4. Kulkarni, V.G. Modeling and Analysis of Stochastic Systems, Chapman and Hall Publications, UK (1995) .
5. Meyerdirk, D. E. and L. W. De Chi. "Models for Minimizing Risks of Dangerous Pests: The Pink Hibiscus Mealybug and Papaya Mealybug" Proceedings of the Caribbean Food Crops Society, Grenada. 39 (2003): 47-55.
6. Michaud, J.P. "Three Targets of Classical Biological Control in the Caribbean: Success, Contribution and Failure", (2002), URL: (http://www.bugwood.org/arthropod/day5/Michaud.pdf)
7. Moffitt, M. J. "Economic Risk to United States Agriculture of Pink Hibiscus Mealybug Invasion", A Report to the APHIS, USDA under Cooperative Agreement No. 98-8000-0104-CA at the University of Massachusetts, Amherst (1999).

8. Persad, A. and A. Khan "Comparisons of Life Table Parameter for M. Hirsutus, *A. Kamali*, C. Montrouzieri and S. Coccivora", BioControl - 47 (2002):137-149.

9. National Agricultural Statistics Service. Various Tables (2004): (http://www.usda.gov/nass/pubs/estindx.htm)

10. Sagarra, L. A., and D. D. Peterkin. Invasion of the Caribbean by the Hibiscus Mealybug, *Maconellicoccus hirsutus* Green (Homoptera: Pseudococcidae): Phytoprotection. 80, (1999) : 03–113.

11. USDA-APHIS. "M. Hirsutus (Green): Simulation of Potential Geographical Distribution Using CLIMEX Simulation Model", Internal Document, (1998).

12. USDA-APHIS (2003): (http://www.aphis.usda.gov/oa/pubs/PHMpaler.pdfT)

13. Zettler, J.L, P.A. Follett, R.F. Gill. "Susceptibility of Maconellicoccus Hirsutus (Homoptera: Pseudococcidae) to Methyl Bromide" Journal of Economic Entomology: vol. 95, No. 6, (2002): 1169-1173.

14. Zimmerman, K. M., J. A. Lockwood, A. V. Latchininsky . "A Spatial Markovian Model of Rangeland Grasshopper Population Dynamics: Do Long -Term Benfeits Justify Suppression of Infestations?" Environmental Entomology, Vol. 33, No. 2, (2002) :257-266.

Table 1: Biological Parameters for PHM and *A. Kamali*

Biological Parameters	*PHM*	*A. Kamali*
Intrinsic rate of growth (rm)	.0801	.3301
Doubling Time (T)	8.63	2.09
Finite Rate of Increase (λ)	1.0834	1.39

Source: Persad and Khan (2002). Intrinsic rate of growth and finite rate of increase are related as $\lambda = e^{rm}$. The doubling time of the species is defined as $T = Ln(2)/rm$

Table 2: Annual Average Value of Crops that are Hosts to the PHM (in 2003 US$ 1000)

	Vegetables	Avocado	Citrus	Cotton	Peanuts	Soybean	Nursery
Florida	1,075,513	14,505	1,379,173	26,567	48,267	1,650	1,006,648.647
US	8,801,959	378,540	2,258,104	3,696,162	747,668	14,236,502	5,381,542.322
CLIMEX-STATES*	6,233,834	363,655.7	878,931.3	2,896,326	634,557.8	71,2246	194,197.853

*These are the eleven States predicted by the CLIMEX model, minus Florida
Source: National Agricultural Statistics Service

Table 3: Expected Fraction of Damages from PHM Infestation

	Vegetables	Avocado	Citrus	Cotton	Peanuts	Soybean	Nursery
Florida	.04	.3	.04	.01	.2	.2	.05
US	.04	.3	.04	.01	.2	.2	.05

Source: Moffitt (1999)

Table 4: Expected Average Damage in Dollar Amounts (in 2003 US$ 1000)

	Vegetables	Avocado	Citrus	Cotton	Peanuts	Soybean	Nursery
Florida	43,021	4,351	55,167	266	9,653	330	50,332
US	352,078	113,562	90,324	36,962	149,534	2,847,300	269,077
CLIMEX STATES	249,353	109,097	35,157	28,963	12,6912	28,490	97,075

Table 5: Expected Annual Damages from PHM by Moffitt (in 2003 US$ 1000)

	Vegetables	Avocado	Citrus	Cotton	Peanuts	Soybean	Nursery
Florida	40,587	3,400	66,958	240	*	*	58,537
US	214,095	72,937	104,176	43,025			247,383

*Not Considered.

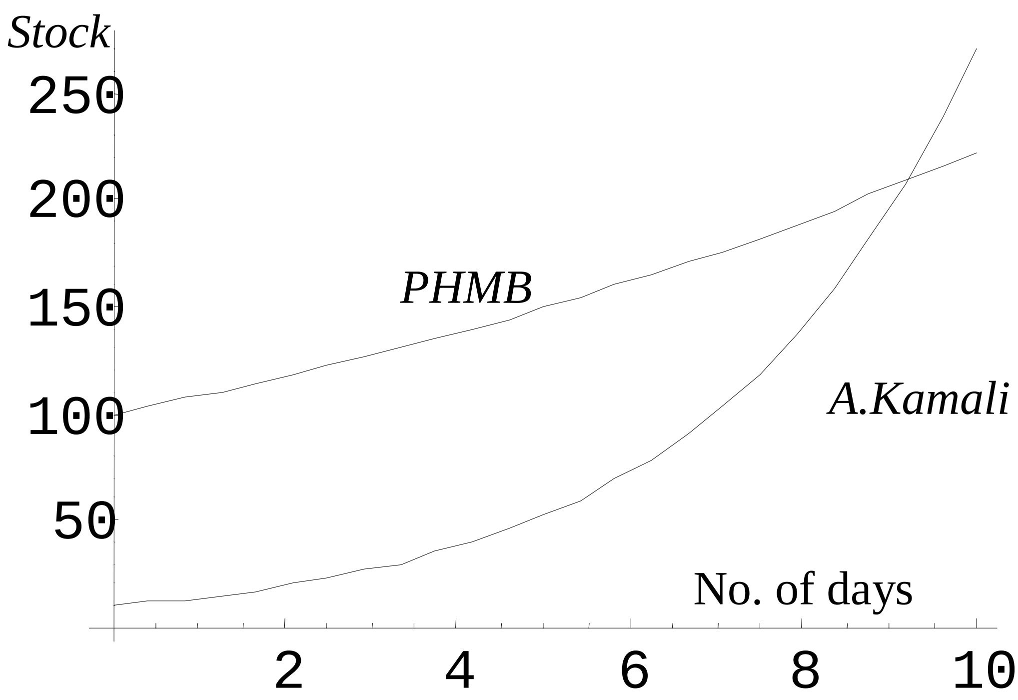
Table 6: Total Annual Average Damages to Crops (in 2003 million US$)

	Mottiff	This Study
Florida	169,722	162.856
US	681,616	1,580.997
11-States, excluding Florida		675.047

Table 7: Sensitivity Analysis (in 2003 million US$)

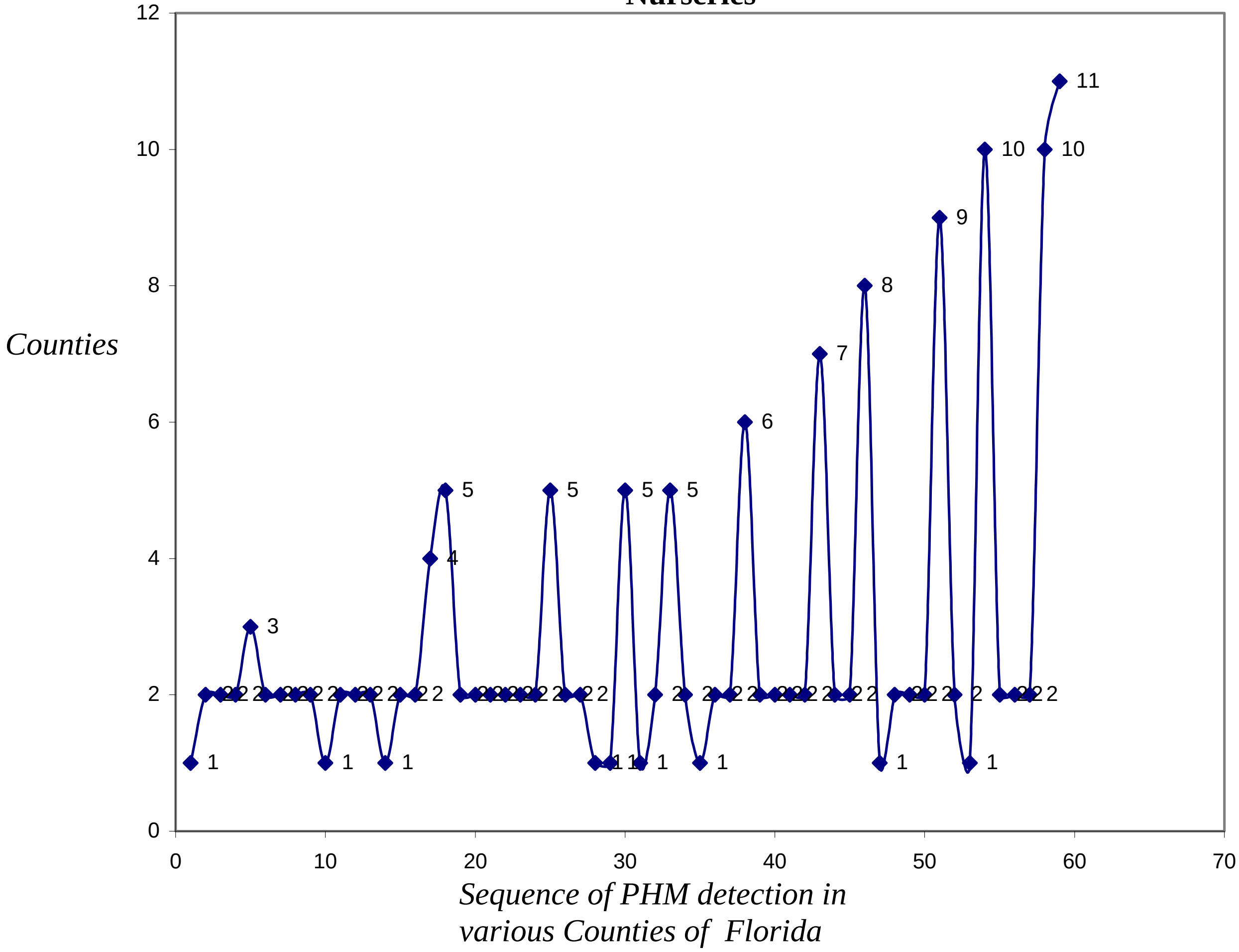
Base Case	Case 1: $a_i = 12.33$, $d_b = 1/(3*49)$	Case 2: $\delta_a = 2$ $\delta_b = 2$	Case 3: $b_e = 12.33$	Case 4: $a_i = 12.33$ $d_b = 12.33$	Case 5: Cost of quarantines=1/2 of the base case
867.580	1,458.73	846.101	1,490.25	2,325.2	458.937

Figure 1: Time Paths of PHM and *A. Kamali*



Note: Figure 1 compares the growth in stock over time for PHM and its predator A. Kamali. Note that the population of A.Kamali overcomes the PHM population in just ten days even though its starting stock is much lower.

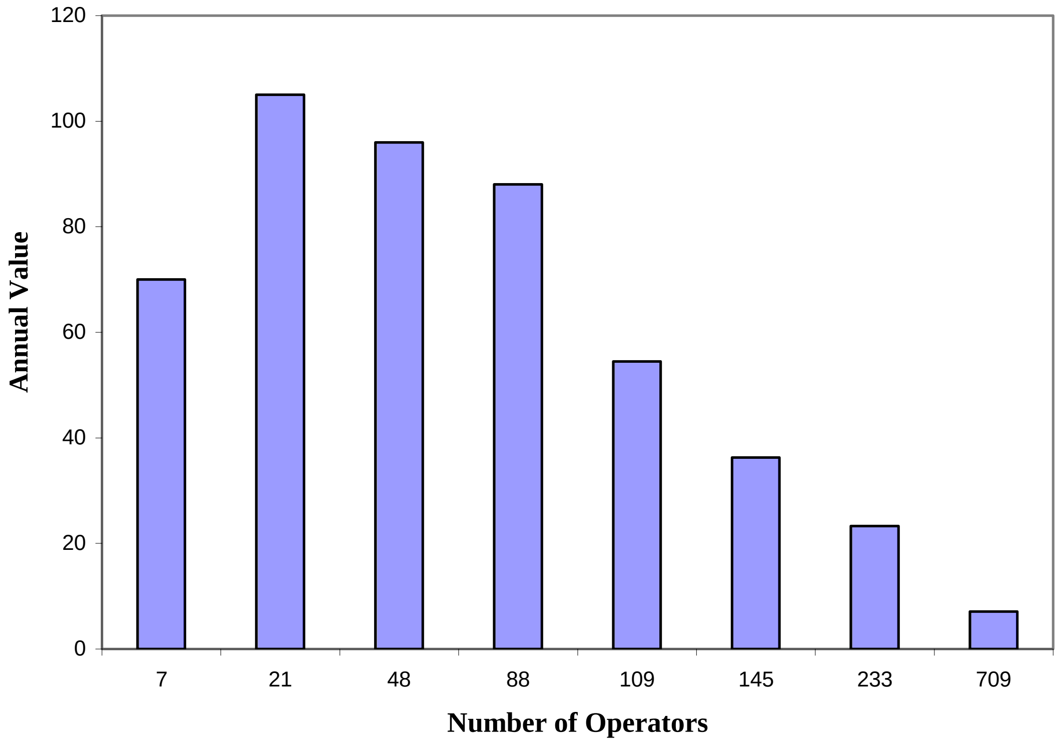
Figure 2: Sequnce of Infestation and Quarantine in Florida Nurseries



Source: Clark (2004)

Note: Figure 2 shows the pattern of infestation in various counties of Florida. The X-axis denotes the order of detection over time and the Y-axis denotes the particular county in which PHM was detected. For instance, the first dot (numbered 1) represents the first case of detection in Broward county. The counties are numbered as: 1-Broward, 2-Dade, 3-St. Lucie, 4-Brevard, 5-Palm Beach, 6-Pinellas, 7-Collier, 8-Desoto, 9-Lee, 10-Hillsborough

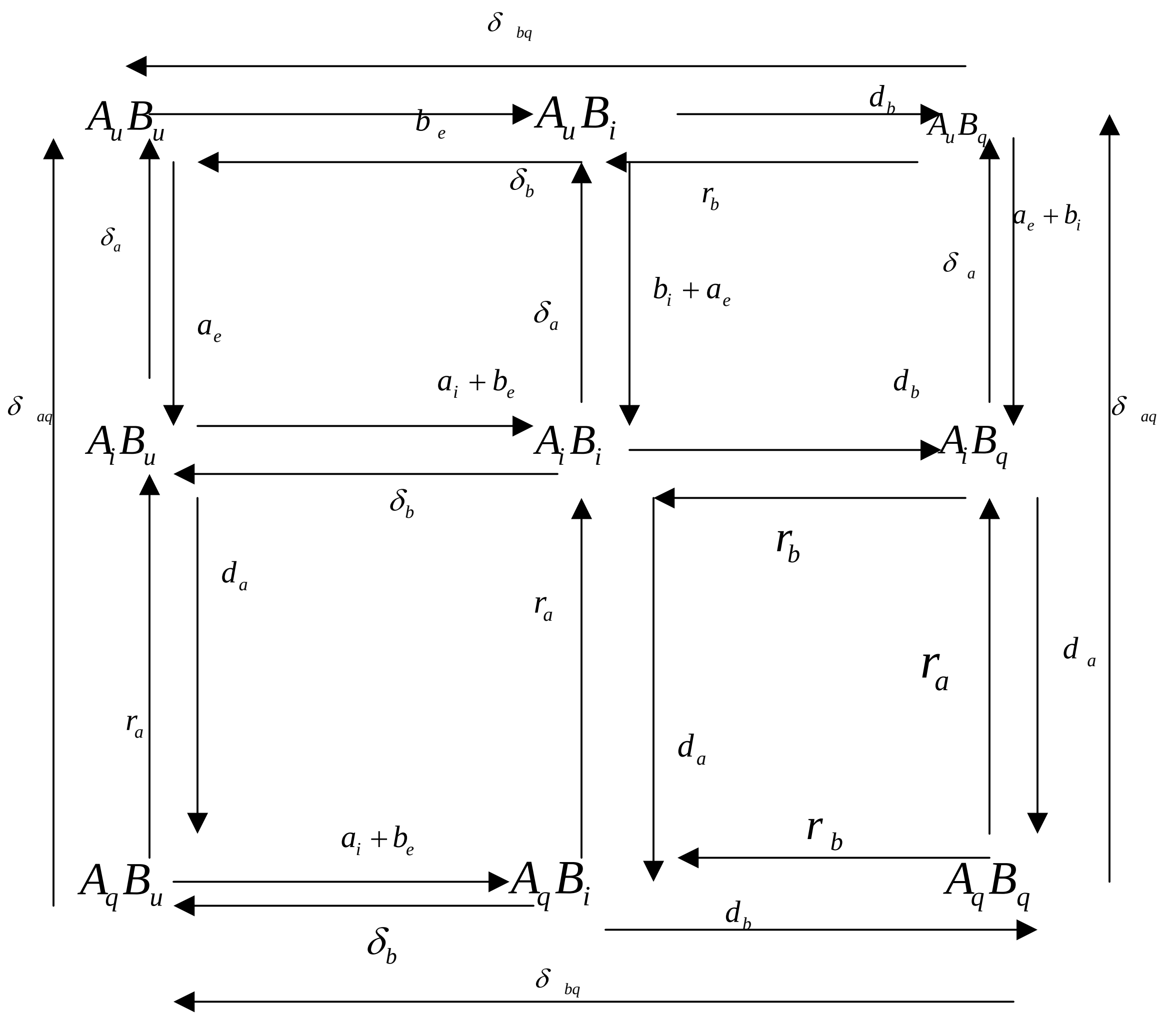
Annual Value of Nurseries in Florida



Source: Drawn from National Agricultural Statistics Service Figures

Note: Figure 3 matches the number of nursery operators in Florida with their annual value of sales in 2003.

Figure 4: Rate Diagram [6]



Note: In this figure the arrows demonstrate the linkages between two states of the system. There are nine possible states of the system. However, it is not possible to move directly from any one state onto all other states. The parameters reflect the rate at which this change in states is made possible. For instance, r_a is the rate at which the state of the system could change from A_qB_u to A_iB_u. That is, region A turns into an infested state at the rate r_a per unit time, whereas there is no change in the state of region B during that period. Alternatively, it can be stated that the system spends, on average, $1/r_a$ amount of time in A_qB_u before moving to state A_iB_u

Figure 5: Generator Matrix

	A_uB_u	A_uB_i	A_uB_q	A_iB_u	A_iB_i	A_iB_q	A_qB_u	A_qB_i	A_qB_q
A_uB_u	*	b_e	0	a_e	0	0	0	0	0
A_uB_i	δ_b	*	d_b	0	$b_i + a_e$	0	0	0	0
A_uB_q	δ_{bq}	r_b	*	0	0	$(a_e + b_i)$	0	0	0
A_iB_u	δ_a	0	0	*	$a_i + b_e$	0	d_a	0	0
A_iB_i	0	δ_a	0	δ_b	*	d_b	0	d_a	0
A_iB_q	0	0	δ_a	δ_{bq}	r_b	*	0	0	d_a
A_qB_u	δ_{aq}	0	0	r_a	0	0	*	$b_e + a_i$	0
A_qB_i	0	δ_{aq}	0	0	r_a	0	δ_b	*	d_b
A_qB_q	0	0	δ_{aq}	0	0	r_a	δ_{bq}	r_b	*

Note: The generator matrix denotes the rate at which transition takes place between states. For instance, the element (b_e) under the row A_uB_u and the column A_uB_i represents the rate at which rest of the US gets infested by PHM arriving from regions outside the US. The elements marked star in any row are the negative sum of departure rates out side the state represented by that row.