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An Agent-Based Model of Border Enforcement for Invasive Species Management

by

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Abstract

This thesis examines ways in which invasive species risk can be managed through the use of border enforcement policies. Building upon a recent theoretical model of border enforcement and invasive species risk and incorporating a spatially explicit damage function, this thesis develops an agent-based model (ABM) to examine the interactions between heterogeneous importers and border inspection agents in order to examine the scenarios under which invasive species risk can be reduced.

Results of the model demonstrate the importance of balancing inspection rates with the ability to conduct successful inspections. They also stress the need for consistent standards amongst different ports. The results indicate ways in which inspector behavior and choices influence and encourage importers to select appropriate levels of pretreatment efforts through the inspectors' use of fines and management of discovered infected shipments. Lastly, the results present the effects of market influences such as pretreatment costs on importer choices.

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Chapter 1: Introduction[1]

Rapid integration of the world in the last few decades has seen a marked increase in the flow of goods and services across borders. While there have been many benefits to this increasingly interconnected marketplace, it has not been without complications. One such consequence has both ecological and economic implications: invasive alien species (IAS). This thesis will examine previous research on the economics of invasive species, as well as discuss a model of importer behavior and border enforcement as it relates to the issue of invasive species, and use this model as the basis for the creation of an agent-based model of border enforcement for invasive species management.

1.1 Previous Research

1.1.1 Prevention versus control

The two primary strategies for management of invasive species are mitigation (prevention) and adaptation (control). Mitigation strategies take place before the invasive species have been introduced and are aimed at reducing the probability that an invasion takes place. Adaptation strategies can take place at any time during the invasion process and are aimed at reducing the magnitude of an invasion rather than the probability of its occurrence (Perrings 2005). In the past, more emphasis was placed on adaptation in the form of eradication and postinvasion control (Horan et al. 2002).

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[1] Sections of this chapter have been published. Holly A. Ameden, Sean B. Cash, D. Angele Vickers, and David Zilberman. 2007. "Economics, policy, and border enforcement of invasive species." Chapter 3 in *Canadian Perspectives on U.S. Policy*, Constance Smith, ed. Edmonton, Alberta: Institute for United States Policy Studies.

Previous research has examined both prevention and control in order to determine the most effective ways to deal with biological invasions. Olson and Roy (2002) examined the economics of controlling a biological invasion and noted that the outcome depends on the distribution of environmental disturbances, the discount rate, the marginal damages from the invasion, and the marginal costs of control. Olson and Roy (2002) limited their work to "primarily focus on invasions for which the optimal policy always involves some level of control" (page 1312) and found that for small invasions "the marginal costs of control are balanced against the infinite geometric sum of intrinsic marginal damages [but] for large invasions, it is the interaction of costs and damages with the discount rate and the invasion growth rate that determines whether eradication is optimal or not" (pages 1314-1315). Kaiser (2006) asserted that in determining the optimal solution to combat invasive species, there are likely to be many corner solutions where there may be more cases where the optimal solution is complete eradication or extinction, or where the accommodation of the invasive species with no control efforts at all is the best choice given the costs and benefits involved.

Perrings (2005) considered how to model mitigation and adaptation strategies and identified situations in which each strategy would be efficient and effective. His results showed that the optimal strategy is the one in which the expected marginal effects of mitigation are equal to the marginal effects of adaptation. Olson and Roy (2005) examined the optimal prevention and control policies with the objective of minimizing the expected social costs and concluded that "the optimal control balances the marginal costs of control against the expectation of random marginal damages associated with the growth in the last unit of the invasion that remains after control" (page 493) and that "the incentives for control increase with the invasion growth rate [which] in turn, stimulates more prevention since the two policies act as substitutes to reduce damages" (page 495).

While some researchers focus on obtaining the optimal balance between prevention and control, others focus more specifically on one management strategy or the other. Horan et al. (2002) designated invasive species a form of 'biological pollution' and focused on the use of preinvasion controls. They noted that using decision models based on standard expected utility theory will not be very effective because they are insensitive to the low probability high catastrophic risk that can be characteristic of invasive species. Standard expected utility models should not be used because "the probability of 'very unlikely' outcomes [tend] to be either overestimated or set equal to zero" (Horan et al. 2002, 1304). Horan et al. (2002) suggested using performance-based incentives or limits which, while potentially difficult to administer, can minimize the risks of invasions and for limits can be set uniformly across firms.

As mentioned, discount rates play an important role when it comes to the risk involved in the prevention or control of invasive species. The risk and time preference of policy managers can affect the outcome of the policy analysis. A risk-averse manager places more value on the certain benefits that come from using control policies rather than the uncertain benefits of prevention policies.

Such managers would rather use control policies because they can see the benefits of their actions whereas with prevention policies the benefits are not directly observable – they will only be able to observe the failures with a lack of such policies or if the policies fails. Finnoff and Shogren (2004) examined how changes in managers' preferences affect the optimal choice of prevention and control. Their results showed that managers who exhibit less myopic and less risk-averse behavior are those who are more likely to invest in more prevention which results in a higher social welfare than those managers that demonstrate more myopic and more risk-averse behavior. Finnoff et al. (2007) found that more risk-averse managers choose to use more control policies for invasive species despite the fact that social welfare would increase if more prevention was used. At lower levels of prevention, the probability of invasions increases so prevention seems to be an attractive option. However, prevention efforts may not always be able to distinguish between introductions that are dangerous, beneficial or harmless, and may not prevent an invasion (Finnoff et al. 2007).

1.1.2 Bioeconomic modelling

Because of the interplay between the biological and economic aspects of invasive species, the use of bioeconomic models can be helpful in making policy decisions. Integrating biological and economic models allows for feedback mechanisms which help present a more realistic image of the issue. Older approaches to the modelling of invasive species only included economists stepping in after the damages had occurred to determine the monetary value associated with the changed state using a "damage function" approach (Shogren et al. 2006). This implied "that the economic system and the ecosystem affect each other in a one-sided way" (Shogren et al. 2006, 12). However, more recently, there has been a move to examine the issue of invasive species in a bioeconomic context (Finnoff et al. 2006). Some modelling approaches that have created "an explicit analytical framework to integrate and account for feedbacks" (Shogren et al. 2006, 12) include the Bioeconomic Endogenous Risk-Stochastic Dynamic Programming (SDP) model developed by Leung et al. (2002), the Optimal Control Approach which is illustrated by Olson and Roy (2002) and the General Equilibrium Ecosystem Modelling (GEEM) developed by Finnoff and Tschirhart (2003, 2005).

Using bioeconomic models to help determine policy choices raises several further considerations. Finnoff et al. (2006) highlighted the issue of how to determine the depth to which a model should be in integrating biology and economics and the tradeoffs that come with their use. They noted that the level of integration "depends on the number of contact points between the systems and the indirect effects within the systems" but in increasing the integration "it is necessary to make other simplifying assumptions" (Finnoff et al. 2006, 149). Shogren at al. (2006) argued that bioeconomic models could be enhanced and strengthened by blending them with nonmarket valuation with respect to the damages, both human and environmental, caused by invasives. Using bioeconomic models can give a more complete picture of what is taking place and lead to a more appropriate policy choices than by using either a biological or economic model alone.

1.1.3 Agent-based modelling

Agent-based models (ABM), also referred to as artificial worlds (AW), individual-based modelling (IBM), agent-based computational economics (ACE), agent-based computational demography (ABCD), social simulation, bottom-up modelling or artificial societies, are increasingly being used in the social sciences to study complex adaptive systems. They are “computer-implementable stochastic models, which consist of a set of ‘microlevel entities’ that interact with each other and an ‘environment’ in prescribed ways” (Lane 1993, 177). In an agent-based model, there are independent, decision making actors which assess situations, make decisions and interact with one another based upon a set of given rules. They are created to “understand properties of complex social systems through the analysis of simulations” (Axelrod 1997, 3). Simulations are analyzed inductively, but rather than examining patterns in empirical data from the real world, patterns are discovered in the data created from the set of given rules in the simulation and rather than providing an accurate representation of a particular empirical event, they are meant to inform and enrich the understanding of the processes (Axelrod 1997). According to Bonabeau (2002), agent-based models are perfect for modelling risk. While agent-based models have previously been used in ecology, business, political science, sociology and economics, to date, there has not been an agent-based model created to examine border enforcement behavior and its effect on invasive species risk.

1.2 Research Objectives

This thesis aims to extend previous research on the economics of invasive species. It will focus on importer behavior (decision making and responses) under different inspection/enforcement regimes. This thesis will examine the effects of border enforcement and inspection policies on the introduction of invasive species.

The objective of this thesis is to use a recently developed theoretical model of both intended and unintended importer response to different inspection/enforcement regimes to inform the development an agent-based model of border enforcement for the management of invasive species risk. The model will be further enhanced by the creation and incorporation of a spatially explicit damage function. The goal of this thesis is to then be able to use this framework to evaluate the impacts of importer-type-specific and port-specific enforcement regimes for a given commodity, enabling regulators to improve both the allocation of scarce enforcement resources and the effectiveness of current enforcement policies. The use of this framework will simulate outcomes from various policy options available to border enforcement agents in order to reduce damages created by an invasive species for a given commodity and an associated invasive species. Furthermore, the agent-based model framework developed for this project will provide an adaptable tool that can be used by policymakers to answer further questions concerning border enforcement and invasive species risk.

1.3 Thesis Structure

This thesis will be organized into seven chapters including this introductory chapter. The next chapter takes a more thorough look at the previous literature on the effects and economics of invasive species as well as provides an overview of the commodity and species that will be incorporated into the agent-based model. The third chapter introduces the theoretical model of border enforcement, importers and risk created by Ameden, Cash and Zilberman (2007) which provides this structure for the agent-based model and discusses the spatially explicit damage function model underlying the agent-based model. The fourth chapter provides the background on the use and suitability of agent-based modelling as the appropriate tool for this exercise. The fifth chapter explains the development of the agent-based model as well as its characteristics. Chapter six reports and analyzes the results of the agent-based model as well as outlines policy implications. Finally, chapter seven will provide the summary and conclusions of this work as well as discuss potential extensions of this work.

Chapter 2: Literature Review and Background[2]

This chapter provides a brief introduction to the issue of invasive species including the definition and explanation of an invasive species, the economic implications of invasive species as well as the policy instruments that have previously been examined for their management. This chapter also provides the overview, background and justification of the chosen agricultural commodity, its location and one of its associated invasive species. This information is used to inform the structure of the agent-based model created in this thesis in order to provide a scenario for study that is as realistic as possible.

2.1 Invasive Species Background

In order to be identified as an invasive species, a species must pass through four stages, which can be summarized as follows: "(1) it must be imported to an area where it is not native; (2) it must be introduced into the wild; (3) it must become established with a self-sustaining population; and (4) it must be a pest which means that it must trigger costs to humans or ecosystems that outweigh any attendant benefits" (Shogren and Tschirhart 2005, 267, following Williamson 1996). The rate at which invasive species have been introduced has been referred to as the 10-10-10 rule by Williamson (1996). That is, approximately 10% of imported species become introduced, 10% of those introduced species become established and approximately 10% of those established species become pests. In the case of the United States, there have been approximately 50,000 non-native

[2] Sections of this chapter have been published. Holly A. Ameden, Sean B. Cash, D. Angele Vickers, and David Zilberman. 2007. "Economics, policy, and border enforcement of invasive species." Chapter 3 in *Canadian Perspectives on U.S. Policy*, Constance Smith, ed. Edmonton, Alberta: Institute for United States Policy Studies.

species introduced, approximately 5000 of which that have established with about 500 of those becoming classified as invasive species (Pimentel et al. 2000). Introductions of non-native pests (also commonly referred to as 'exotic', 'non-indigenous' or 'introduced') can be unintentional; intentional, such as importing exotic plants for sale; or deliberate, e.g., as an act of terrorism.

2.2 Economics of Invasive Species Management

Losses associated with invasive alien species can accrue in several ways. The Food and Agricultural Organization has identified six types of direct and indirect economic impacts of invasive species (Evans 2003). These are production, price and market effects, trade, food security and nutrition, human health and the environment, and financial impacts. In the case of ecological change or damages to the natural environment, losses are projected mainly in the form of changes in quality and quantity of water or soil, loss of biodiversity and resiliency, and productive resource losses (Kaiser 2006). According to Pimentel et al. (2005), the loss of biodiversity caused by invasive species can be severe. They report that 42% of the species on the United States "threatened" or "endangered" species lists are there either primarily or in part due to competition from invasive species (Pimentel et al. 2005). Production impacts, for example, are felt through a loss in efficiency of agricultural production systems and are considered to be the most direct. Financial costs, on the other hand, may include costs associated with inspections, monitoring, prevention, and response (Evans 2003) or damages to facilities such as buildings, plants and equipment.

In the United States, Jenkins (2002) reported that the federal government spent as much as $613.5 million in combating invasive species in the 2000 fiscal year. Simberloff (1996) reported that non-indigenous plant pests and the associated costs of controlling them results in close to a 25 percent loss in agricultural output in the United States. In one study, Pimentel et al. (2005) estimated costs of invasive species to be approximately $120 billion (which includes the costs of damages, expenditure on control, expenditure on pesticides and fungicides and the break down of losses due to invasive species) while in a previous study by Pimentel et al. (2000) costs were estimated to be as high as approximately $137 billion (which includes losses and damages as well as control costs for plants, mammals, birds, reptiles and amphibians, fishes, arthropods, mollusks and microbes). Pimentel et al. (2005) acknowledged that their estimates would have been much higher if they were able to "assign monetary values to species extinctions and losses in biodiversity, ecosystem services, and aesthetics" (page 283). These estimates point out the necessity of using non-market valuation techniques in order to determine the full costs that invasive species impose on society. The difficulties in estimating the costs and damages from invasive species present a problem when it comes time to develop policies for their prevention and/or control.

In addition to the difficulties in trying to measure the costs invasive species impose and their interference in agricultural production, it is difficult to track and manage the human activities that foster and promote their introductions Horan et al. (2002) noted that most IAS invasions are caused by human activities, primarily trade and travel. A country may set itself up to be more or less susceptible to an invasion depending on the openness of its economy, the volume of trade it engages in and with whom, its institutions and the role played by agriculture, forestry and tourism in its economy (Perrings et al. 2002). Increasing the volume and level of trade while at the same time relaxing regulations to encourage trade has led to greater movement of potentially invasive species across borders (Perrings et al. 2002). Decisions made by individuals, firms, and the government help determine, to some extent, the risk of an invasion.

One important aspect of invasive species and their management that can further complicate the issue is that the provision of their prevention and control can be seen as a weakest-link public good. A public good occurs when a good is neither rival in consumption (use of the good by one person does not reduce the amount of the good being available to be used by others) or exclusive (one person's use of the good does not preclude others from enjoying the benefit of the good). Because invasive species prevention or control is a public good, there is a strong incentive to free ride – to enjoy the benefits without incurring the costs. This can prevent optimal provision of the good; "if left to the market, the control of potentially invasive pests and pathogens would be undersupplied. There would be less control than is socially desirable" (Perrings et al. 2002, 4). The weakest-link nature implies that the system is only as strong as the least effective provider of invasive species prevention or control (Horan et al. 2002).

Another complication that arises with invasive species and their associated damage is that they can often be characterized as externalities. The costs of the invasive species, whether in the form of increased market prices, control measures, or ecosystem losses, are not borne solely by those whose activities are responsible for their introduction but rather by a larger portion of society. Addressing such negative externalities requires that those whose actions create the externality be required to face the costs of their actions, to "internalize" the externality (Perrings et al. 2005). In order to help correct these market failures, governments need to play a role in the prevention and control of invasive species. However, this role can become complicated by the fact that invasive species can be a local, regional, national or international issue, and as such may require many different groups to work together.

A third characteristic of invasive species is that they can lead to "potentially catastrophic and irreversible consequences . . . [with] low (but largely unknown) probabilities" (Horan et al. 2002, 1304). Thus a decision maker's preference for risk influences the rate at which they discount the future costs and benefits of prevention and control. The choice of the discount rate used in such calculations may have a large impact on which policy and management strategy is chosen – the optimal strategy chosen under one discount rate may differ markedly from the optimal choices under another discount rate reflecting different risk preferences.

2.3 Policy Instruments for Invasive Species

Several studies have examined specific policy instruments for addressing trade-related invasive species risk. Potential policy instruments that have been explored for prevention and control of invasive species include uniform technology standards, tradeable permits, fees and taxes as well as inspections and tariffs.

Tradeable permits may have benefits over uniform standards insofar as they give firms the flexibility to control the costs associated with their reduction of potential invasive species introduction which leads to greater efficiency. Horan and Lupi (2005) considered whether tradeable permits may be a viable alternative for addressing the 'biological pollution' of invasive species in the Great Lakes. While they acknowledged that "because there is no readily available method of directly measuring IAS emissions, [the permits] cannot be directly traded" and also that their model is limited by a lack of information of bioinvasion risks and biosecurity costs, their results show that using permits does in fact have the potential to be more efficient than uniform technology requirements (Horan and Lupi 2005, 291). While further work is needed to determine the viability of this policy tool for invasive species, the use of tradeable permits remains an interesting choice for invasive species control because they could allow firms to control how to reduce their potential to introduce an invasive species whereas firms may have no such control with uniform standards. However, to some, the use of tradeable permits appears to confer to the holder the right to pollute. This comes into conflict with the "polluter pays" principle.

In his article, Jenkins (2002) argued that the polluter should be held responsible for the pollution that it causes. Jenkins compares the "biological pollution" of invasive species to that of an oil spill and suggests that the costs should be borne by the industries which contribute to invasive species introduction. He suggested six ways in which to do so: "insurance requirements, bonding requirements, civil fines, criminal penalties and fines, fees, and corrective taxes" (Jenkins 2002, 69). According to Jenkins (2002), the most practical of these is a fee because it does not face a time lag problem nor face the politics of a tax. This does not suggest that this fee should take the place of existing user fees for such things as quarantine and inspection but rather could be used to "support inspection, monitoring, prevention, and quick response efforts". It would also help to internalize the externality caused by invasive species due to industry activities.

Jenkins' suggestion of using a fee as a way to make industries pay has been explored in the travel industry. Beginning in late November 2006, the U.S. will employ a fee on airline travel from Canada to the U.S. Canadian airline travelers will be faced with an additional $5 US fee which will be used to help cover the costs of invasive species that are brought into the U.S. via fruits and vegetables by travelers as well as an increase in the charges levied on commercial vehicles moving from Canada to the U.S. (Alberts and Fitzpatrick 2006). The introduction of the fee, to which Canadian travelers were previously exempt, is in response to the increasing numbers, from 358 in 2001 to 1,520 in 2004, of quarantined materials intercepted by U.S. inspectors (Alberts and Fitzpatrick 2006).

The use of tariffs as a way to combat invasive species introductions is an attractive alternative to economists because the use of a tariff can also help to internalize the externality aspect of invasive species. McAusland and Costello (2004) explored the use of tariffs along with port inspections and found that "the optimal trade tax is positive and tends to increase in the proportion of imports that harbour (or will become) invasive species while the optimal level of port inspections is, after a point, decreasing in that proportion. In fact, once the infection rate passes some threshold, it is optimal to not inspect at all and just charge an appropriately high import tariff" (page 955). They found that the tariff should be set "equal to the sum of expected damages from contaminated units not detected during inspections plus the costs of inspections in the first place." If the proportion of infected goods is high enough, it was found that it is better to charge a tax (McAusland and Costello 2004). This does present difficulties, however, in determining what the expected damages will be and deciding which damages to include in the calculation. Perrings et al. (2005) also support the use of tariffs (when combined with supporting biosecurity-enhancing measures in exporting countries) in combating invasive species.

To further extend the work on the economics of invasive species, this thesis seeks to examine one of the contributing factors for their introduction; trade. It looks to examine the effects of border enforcement behavior on the ability to reduce invasive species risk. Specifically, it examines the inspection vs. non-inspection decision, the ability of inspectors to conduct a successful inspection, the decision whether to treat or destroy a shipment that is found to be infected and the rate at which to fine an importer for an infected shipment. This research aims to determine the conditions under which an importer will chooses to pretreat their shipments as well as how much effort they choose to invest in their pretreatment efforts. Ideally, the model should provide policymakers guidelines on the frequency of inspection, the effects of increasing the success rate of inspections, the effects of treating or destroying an infected shipment and the level at which to fine an infected shipment.

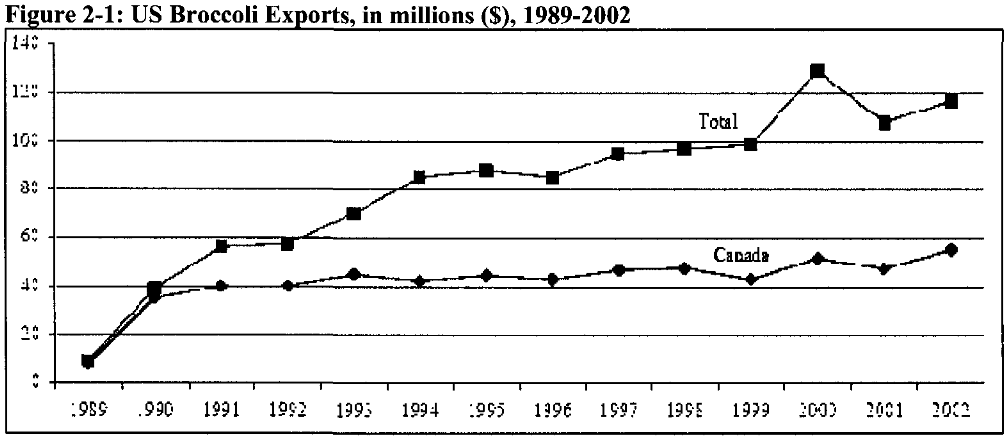
2.4 Model Commodity, Location and Invasive Species

In order to extend the theoretical model proposed by Ameden, Cash and Zilberman (2007), a commodity, location and invasive species was selected to base the agent-based model on. Based on the data provided by the Work Accomplishment Data System (WADS) from the United States Department of Agriculture (USDA)-Animal Plant and Health Inspection Services (APHIS), the commodity selected was broccoli, the location of interest was California and the invasive species of concern was the crucifer flea beetle (*Phyllotreta cruciferae, Coleoptera: Chrysomelidae*). Specifically, this thesis examines shipments of broccoli from Mexico to California via two ports – Calexico and Otay Mesa to see how these shipments may increase the risk of damage to California broccoli crops through the introduction of self-sustaining crucifer flea beetles in the area.

2.4.1 US/California broccoli and trade

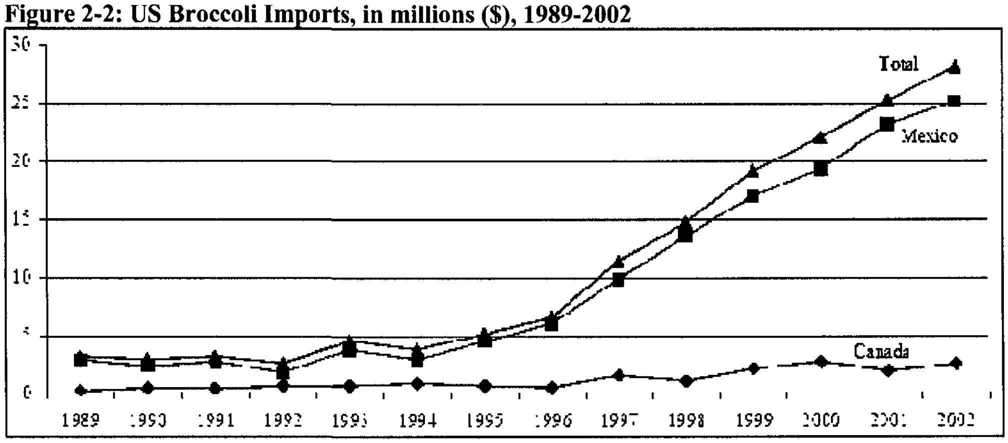
The US is both an exporter and importer of broccoli. They exported over $116.5 million worth of broccoli in 2002 with over 47 percent of the exports going to Canada (Brunke and Stanford 2003). Broccoli imports, meanwhile, were valued at $28.1 million with 89.4 percent of imports coming from Mexico (Brunke and Stanford 2003). The volume of broccoli trade has been steadily increasing from the year 1989 to 2002 as illustrated by Figure 2-1 and Figure 2-2 below.

Figure 2-1: US Broccoli Exports, in millions ($), 1989-2002



(Brunke and Sumner 2002)
(Source: US Customs Service)

Figure 2-2: US Broccoli Imports, in millions ($), 1989-2002



(Brunke and Sumner 2002)
(Source: US Customs Service)

It will be interesting to see how US imports of broccoli from Mexico change in the upcoming years. Under the North American Free Trade Agreement

(NAFTA), the tariff on Mexican broccoli imported to the US between January 1 and May 31 will be reduced to zero in 2008 while the tariff on Mexican broccoli imported between June 1 and December 31 had already been reduced to zero in 1998 (Brunke and Sumner 2002). Prior to 1994, broccoli tariffs on imports from Mexico were 25 percent (Brunke and Sumner 2002) and as they were reduced, imports from Mexico increased dramatically as seen in Figure 2-2. With the elimination of tariffs on broccoli imported between January 1 and May 31, there may be yet another rise in Mexican broccoli; potentially, increasing the risk of invasive species.

2.4.2 California broccoli production

In 2002, California was responsible for producing approximately 97.5 percent of the total United States broccoli production which amounted to about 1.66 billion pounds of broccoli (Brunke and Stanford 2003). The amount of broccoli acreage in California increased by 41,000 acres between the years 1991 and 2001, despite a slight decline in 2001 (Brunke and Sumner 2002) for a total of 129,000 acres. In addition to an increase in the acreage, there had also been an increase in the quantity of broccoli being produced in California during the same period; from 10 million cwt in 1991 to 18 million cwt in 2001; an increase of 80 percent (Brunke and Sumner 2002).

According to the USDA National Agricultural Statistic Service (NASS 2007), in 2006 there were 128,500 acres of broccoli planted in California, 127,000 of which were harvested and a total value of $599,436,000. Calculating the value of an average broccoli crop in California in 2006 provides a value of $4,719.97. With a loss of 1,500 acres, producers could potentially stand to lose upwards of $7,079,952.76. The data from the years 1998 to 2006 are summarized in Table 2-1 below.

Table 2-1: California Broccoli Planted, Harvested and Value 1998-2006

Year	Acres Planted	Acres Harvested	Acres Lost	Value of Production ($)	Value of Avg Acre	Value of Lost Acres ($)
1998	121,000	121,000	0	454,383,000	3755.23	0
1999	130,000	130,000	0	432,973,000	3330.56	0
2000	133,000	133,000	0	575,349,000	4325.93	0
2001	122,000	122,000	0	439,387,000	3601.53	0
2002	118,500	118,500	0	486,192,000	4102.89	0
2003	120,000	120,000	0	575,224,000	4793.53	0
2004	122,000	122,000	0	587,117,000	4812.43	0
2005	124,000	123,000	1000	519,788,000	4225.92	4,225,918.70
2006	128,500	127,000	1500	599,436,000	4719.97	7,079,952.76

(Source: NASS 2007)

Broccoli is produced in four main areas of California; the Central Coast region, the South coastal region, the San Joaquin Valley region as well as the South Eastern Desert counties. The majority of production occurs in the Central Coast Region (60 percent of overall production) counties of Monterey, San Luis Obispo, San Benito and Santa Clara – the largest production area being in Monterey County. In this region, production takes place year round (CASS 1998).

Broccoli is also produced year round in the second largest production area; the South Coastal Region. This region produces 23 percent of the total broccoli in California, most of which takes place in the county of Santa Barbara (CASS 1998).

The South Eastern Dessert counties of Riverside and Imperial contribute for nine percent of the total broccoli production in California (CASS 1998). In these counties, broccoli is not produced year round. Planting occurs between the start of September and the end of December while harvesting takes place from the end of November until the beginning of April (Crop Profile for Broccoli in California 1999).

The fourth main production area is in the San Joaquin Valley. Eight percent of broccoli production takes place there, mainly in Fresno County (CASS 1998). Planting in this region occurs from mid-July until October with harvests from mid-October until December (LeStrange et al. 1996).

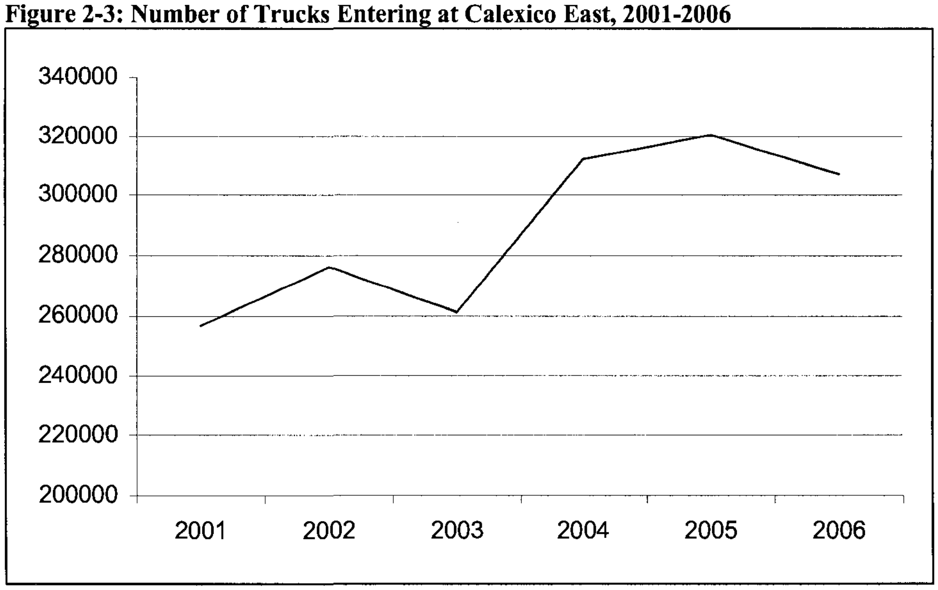
2.4.3 Ports and Inspections

Since 2003, inspection duties in the United States fall under the control of the Bureau of Customs and Border Protection (BCBP), Department of Homeland Security. Prior to 2003, the United States Department of Agriculture's (USDA) Animal and Plant Health Inspection Service (APHIS) were in charge of inspection duties. The inspection process includes pre-clearance, import permits, prescribing pre-import treatment, inspection at ports, quarantines, detection surveys, and eradication programs.

Broccoli is shipped from Mexico to California via land ports (Calexico and Otay Mesa) airports (San Diego and Los Angeles) and marine ports (Long Beach). In this thesis, the focus will on modelling the land crossings at Calexico and Otay Mesa.

Calexico is located in Imperial County just across the border from Mexicali (the capital of Mexico's Baja California state). There are two ports of entry; Calexico West which primarily handles personal crossings and Calexico East which handles commercial and personal crossings. Calexico East averaged approximately 289,000 trucks per year between the years 2001 and 2006 with a high of 320,212 trucks in 2005 as seen below in Figure 2-3 (RITA 2007).

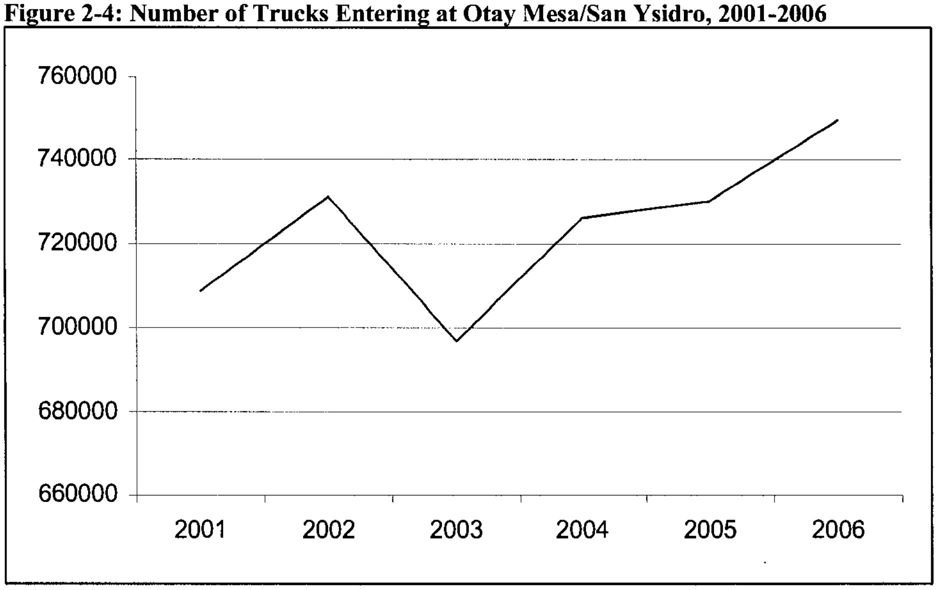
Figure 2-3: Number of Trucks Entering at Calexico East, 2001-2006



Calexico's location has been considered "as the prime link between the interior of Mexico and the major markets along the west coast of the [US] and Canada" (City of Calexico website 2007).

The port of entry Otay Mesa is located in the San Diego County in a rural community within southeast San Diego. It is the largest commercial crossing along the California/Mexico border and handles the second highest volume of trucks with the third highest dollar value of trade amongst all US/Mexico land border crossings (an average of more than $23 billion annual mainly from manufacturing and agricultural industries) (Otay Mesa Chamber of Commerce 2007). Between the years 2001 and 2006, the port Otay Mesa/San Ysidro averaged approximately 724,000 trucks per year with a steady increase in traffic in the last three years as show in Figure 2-4 (RITA 2007).

Figure 2-4: Number of Trucks Entering at Otay Mesa/San Ysidro, 2001-2006



Of the trucks entering the US through this port, 84 percent have destinations outside of the San Diego region; the majority of which (59 percent) stay within California while 25 percent move on to other states; only 16 percent stay within the region (Otay Mesa Chamber of Commerce 2007).

2.4.4 The Crucifer Flea Beetle

The term flea beetle is used to identify many species of beetle which, when disturbed use their enlarged hind legs to jump quickly, whose adults feed on their host plant's leaves and whose larvae usually feed on the host plant's roots (Olson and Knodel 2005). The flea beetles are then further identified by the crops they choose to eat. Flea beetles that feed on *Brassica* crops (which include broccoli (*Brassica oleracea l. var. italica*)) are the crucifer flea beetle (*Phyllotreata cruciferae*) and the striped flea beetle (*Phyllotreta striolata)* (Hazzard 2006).

This thesis examines the effect of the crucifer flea beetle on broccoli crops in California. The crucifer flea beetle was chosen for examination in this thesis because is one of the most potentially damaging pests to broccoli crops in California. It is a non-native insect pest accidentally introduced to the United States in the 1920s from Europe and Asia (Olson and Knodel 2005) and despite the fact that it already exists in the United States, shipments of broccoli from Mexico may accidentally introduce more crucifer flea beetles into the California region (a non-native area) such that they may be able to establish with a self-sustaining population and create a net loss effect on the Californian broccoli industry.

There are four stages in the life cycle of the crucifer flea beetle; egg, larvae, pupae and adult. There is one generation of crucifer flea beetle per year (Olson and Knodel 2006). Adult crucifer flea beetles overwinter until earl spring when temperatures reach about 57°F (14°C) (Hazzard 2006, Olson and Knodel 2006). The adults are small (1/32-1/8in or 2-3mm in length), oval-shaped and blackish with a bright blue sheen (Olson and Knodel 2006). It is the adults that cause the most damage to broccoli crops by feeding on the surface of leaves and stems, leaving small holes often referred to as "shot holes" (Hazzard 2006). Once the overwintering adults have emerged and fed, they begin to lay eggs which are "yellow, oval and about 0.38-0.46 mm long by 0.18-0.25 mm wide, and deposited singly or in groups of three or four adjacent to the host plant's roots" (Knodel and Olson 2002). After approximately two weeks, the larvae, which are approximately 3 mm – 6 mm long cylindrical worms with brown heads and anal plate and tiny legs emerge from the eggs and begin feeding on the secondary roots (Knodel and Olson 2002). It takes the larvae between 25 and 34 days to move on to their next stage of development – the pupal stage. "Pupae are similar in size to the adult and white in color except for the black eyes and the free body appendages, which are visible later in the pupal development" (Knodel and Olson 2002). From this stage, which lasts between seven and nine days, the new generation of adults emerges, feeds and in the fall, move to their overwintering sites to begin the cycle again (Knodel and Olson 2002).

There are strategies available to crop managers which can help mitigate the damages created by the crucifer flea beetle. Hazzard (2006) points out five management strategies that can be used in dealing with crucifer flea beetles. One strategy is to escape them through the use of crop rotation. By moving the spring crops away from where the fall crops were planted, it will be more difficult for the beetle to spread and the farther away the crops can be planted, the greater the chance there is of new damage. This may also be achieved by separating the early and late crops. Another management strategy is to starve them by delaying planting so that the overwintering adults have nowhere to feed or reproduce thus reducing their numbers. A third management strategy that may be used is to kill the beetles through either the use of insecticides or tilling under the crops once they have been harvested. The fourth strategy is to shut them out. One way to shut them out is to use row covers to protect the planting bed. The last strategy provided by Hazzard (2006) is to use some combination of the other four strategies and to provide the crops with good growing conditions so to help increase the plant's survival if it is attacked.

Chapter 3: The Theoretical Model

This chapter seeks to report and explain the theoretical model developed by Ameden, Cash and Zilberman (2007) and highlights their results. The theoretical model presented will be used to provide the basis for the agent-based model in this thesis. The results of the theoretical model are then examined in later chapters to see if they hold true in the agent-based model. In addition, this chapter will also provide an overview of the creation of the spatially explicit damage function that underpins the agent-based model of border enforcement for invasive species management.

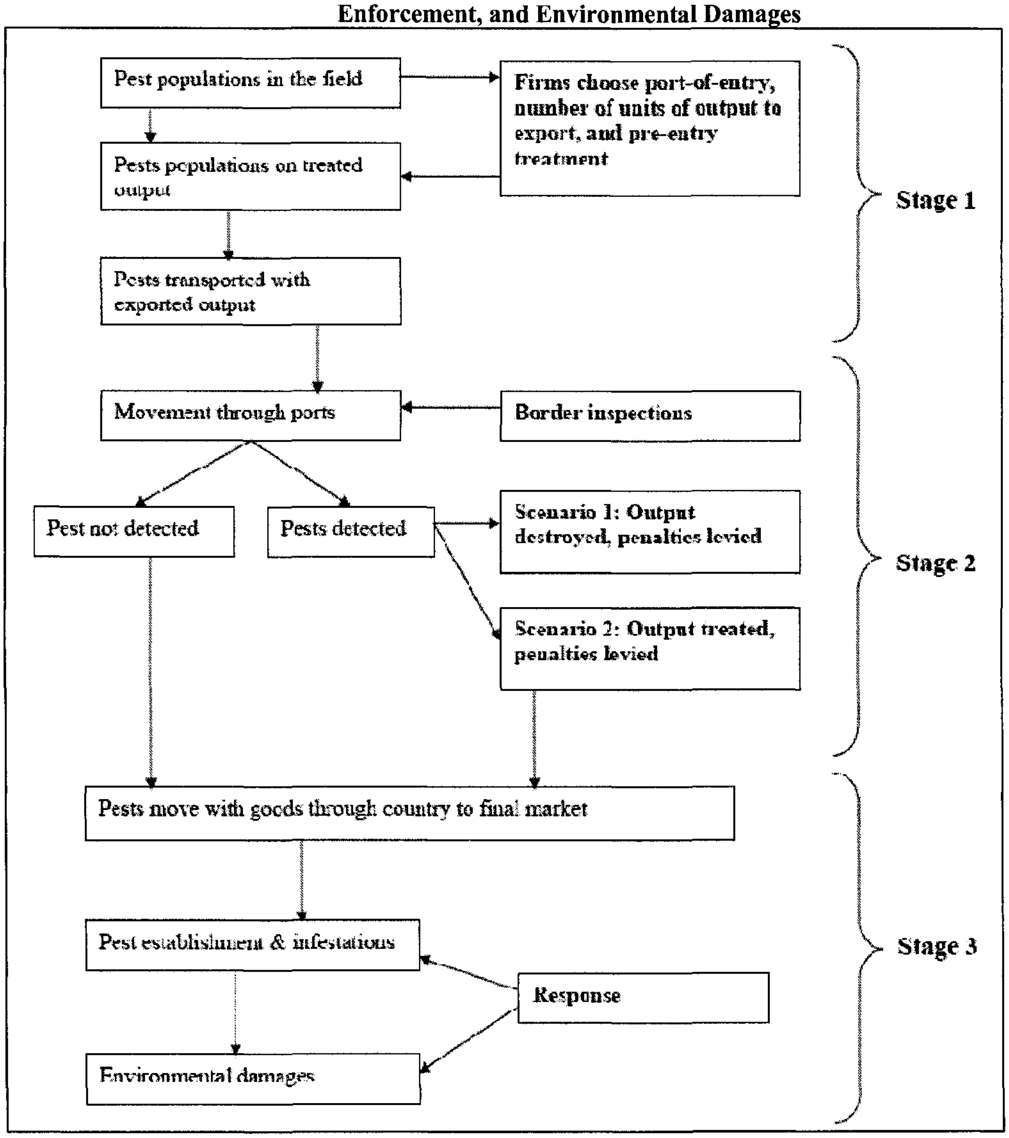
3.1 Model of Importing Firms and Border Enforcement

The theoretical model proposed by Ameden, Cash and Zilberman (2007) seeks to examine the interaction between importers and border enforcement agents and determine conditions under which these interactions may lead to the reduction of trade-related invasive species risk. The model evaluates both intended and unintended importer response to different border enforcement regimes with a focus on firm-specific and port-specific attributes. "This analysis considers two inspection and enforcement approaches for imports of a single commodity (i.e., destruction versus treatment of contaminated goods)" (Ameden, Cash and Zilberman 2007, 35-36). This model fills a gap in the literature by considering "how changes in border monitoring (as opposed to fines and monetary incentives) may result in unintended firm response" (Ameden, Cash and Zilberman 2007, 37).

3.1.1 Stages of the Theoretical Model

The theoretical model moves through four stages. The first stage consists of actions taken by the importing firm. The firm makes decisions on how much of their good to ship, amount of pre-treatment effort to undertake (each firm has an associated initial pest population) and the port through which to ship. The second stage consists of the actions taken by the government inspection agencies. Regulators determine the intensity of inspections and border treatments, and set tariffs and penalties. The inspectors will either detect a pest or they will not. Assumptions made in the model "suggest that higher investment leads to higher discovery but the marginal productivity of investment is decreasing" (Ameden, Cash and Zilberman 2007a, 8). If a pest is detected, there are two potential scenarios that are compared. In the first scenario, infected shipments are destroyed and the importers are required to pay a penalty. In the second scenario, the infected shipments are treated and the importer is charged for both the treatment cost as well as a penalty. There is still potential, however, that the treatment applied by the border enforcement agents may not be completely effective in which case there is still potential for pests to move on to the final market destination. In stage three, the importer's product continues on to the final market and is sold. The last stage of the model reveals the environmental damages that have occurred as a result of the introduction, establishment and infestations of the pest. The stages of the model, with the stages three and four combined, are illustrated in Figure 3-1 below.

Figure 3-1: Model of Pest Population and Movement, Importing Firm Decisions, Border Enforcement, and Environmental Damages



(Source: Ameden, Cash and Zilberman 2007a, 32)

In order to solve the theoretical model proposed by Ameden, Cash and Zilberman, it is necessary to use nested optimization using backward induction. Depending on which enforcement scenario the government chooses to implement (either to destroy or treat infected shipments), the firm determines its level of pretreatment and the quantity of their good to export. The assumptions made on behalf of the firm include profit maximization, given prices for their commodity and the risk that their shipment, if infected, may be discovered.

3.1.2 Results of the Theoretical Model

The theoretical model has five key findings.

1. Increased (decreased) inspection levels, tariffs and penalties always decreases (increases) the optimal level of output chosen by the firm.

As the inspection levels, tariffs and penalties increase, the firm will choose to export a lower level of output because the levels, tariffs and penalties create a decrease in the price the firm receives for its output.

2. As transportation costs increase (decrease) and commodity price decreases (increases), the optimal level of output chosen by the firm is likely to decrease (increase).

As the transportation costs increase and/or the commodity price decreases, the firm will again choose to export a lower level of output because their cost of doing business increases and/or the price they receive for their output is lower.

3. When the enforcement scenario is to destroy rather than treat, the firms will likely have a greater response in terms of optimal output and pretreatment level.

The firm is likely to have a larger magnitude of response to the enforcement scenario of destroy rather than treat because in the destroy scenario, the shipment is removed from the total supply and the firm loses the value of the shipment in addition to the penalties of having an infected shipment whereas if the shipment is treated, it is still part of the supply so the firm is faced only with the penalties and treatment costs of their infected shipment.

4. Increased inspection and penalties may increase or decrease the total point-of-origin treatment depending on certain conditions.

The increase in inspections and fines may increase the point-of-origin treatment due to the fact that it provides incentives for the firm to take greater care of their shipments before shipping them to ports. If there is a greater chance of being inspected, the firm has greater incentives to ensure that their shipment is clean so as to avoid the destruction of their shipment plus the fines or the treatment at the border costs plus the fines for an infected treatment. On the other hand, increased inspection and penalties also have the ability to decrease the overall total point-of-origin treatments due to the fact that the firm may respond by decreasing their output. This will decrease the need for point-of-origin treatment overall.

5. Increased inspection intensity may not lead to an overall reduction in pest risk.

Overall reduction in pest risk may not occur even with increased inspection intensity because of the reaction of the firm. The firm may respond to the increase by shipping less and treating more but when enforcers choose the enforcement scenario of treat, this may not be the case. It will depend "on the efficiency of their treatment technology" (Ameden, Cash and Zilberman 2007, 41).

3.1.3 Summary of the Theoretical Model

The theoretical model proposed by Ameden, Cash and Zilberman models importer behavior as a strategic interaction with border enforcement agents and policy as a management tool in reducing invasive species risk. It demonstrates that importers may choose to respond to increased inspection by either increasing or decreasing pretreatment efforts depending on certain conditions. Shipment quantities are also influenced by the decisions made by the border enforcement agents and policies.

While the model provides several relevant policy implications, it is not without limitations. It does not examine the effects of differences amongst individual firms or ports or provide a mechanism for identifying firms which continually ship infected goods. The agent-based model aims to expand upon the theoretical model by incorporating heterogeneity in the importers and the ports as well as by introducing a learning process to identification repeat violators. The theoretical model presented does not take into account the uncertainty of the pests themselves which plays a large role in determining what level of damages may be associated with scenarios outlined above. To enhance this aspect of border enforcement management of invasive species risk for the creation of an agent-based model a spatially explicit damage function was developed.

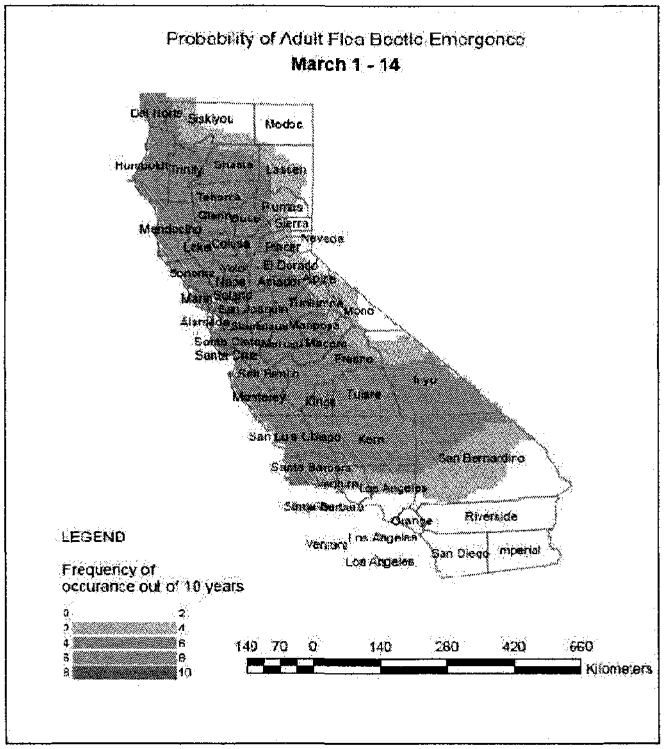
3.2 Spatially Explicit Damage Function

In order to be able to portray the establishment of the crucifer flea beetle in the agent-based model, a spatially explicit damage function was created by Samuel D. Brody at Texas A&M University. Brody (2007) developed a GIS-based spatial damage model that could be used to estimate the damage of pests passing through heterogeneous ports-of-entry using the North Carolina State University (NCSU) and Animal and Plant Health Inspection Services (APHIS) Plant Pest Forecast System (NAPPFAST). A degree-day model to predict the occurrence and spread of the crucifer flea beetle in California was created.

NAPPFAST models plant pests using georeferenced climatological weather data. The system produces maps which illustrate the effects of weather and climate on pest risk or development but does not account for a variety of other factors which may influence risk and development including habitat or soil suitability and makes the assumption that the distribution of the pests are uniform (Magary and Borchert, 2004; Borchert and Magary, 2005). The risk probability maps created by Brody are based on two week periods for one year that represent the frequency of occurrence of the adult crucifer flea beetle out of 10 years and were created using a degree-day model. Brody's analysis was based on the 30 year historical national weather database. "The data is interpreted as the number of times the model parameter (accumulated degree days) occur within a selected time frame (Magary and Borchert, 2004; Borchert and Magary, 2005)[; for] instance, if the degree day accumulation for a specific location occurs 10 years out of 30, then there is 30% probability of occurrence, or 3 out of 10 years"

(Brody 2007, 13). An example of one of the risk probability maps is shown in Figure 3-2 below.

Figure 3-2: Probability of Adult Flea Beetle Emergence March 1-14



(Source: Brody 2007, Appendix 2)

The main factor in degree-day (DD) modelling is temperature accumulation; which is the main weather factor influencing the biology of the pest. "A degree day, also referred to as a growing degree day (GDD) is a unit of measure reflecting the amount of heat that accumulates above a specified base temperature during a 24-hour period" (Brody 2007). In order for the crucifer flea beetle to develop from egg to adult, it requires 456 DD with a base temperature of 51.8°F (11°C) (Brody 2007). Table 3-1 below summarizes the degree-day parameters used in Brody's model.

Table 3-1: Crucifer Flea Beetle Degree-Day Values Summary

	Stage	Degree Day in stage	First entry	Second entry
Overwintering stage	Adult	64	15	79
	Egg	81	80	161
	Larvae	210	162	372
	Pre-pupal	46	373	419
	Pupae	119	420	539
	Adult	64	540	604

(Brody 2007, 10)

3.2.1 Summary of the Spatially Explicit Damage Function

The results of the spatially explicit damage function show that there are higher probabilities of emergence and spread of the crucifer flea beetle in California from January through June with January, February and March being the months in which the probabilities are the highest. The model predicts that the highest probability of damage to broccoli crops will occur in the period of January through March (Brody 2007).

While the spatial damage function created by Brody does include estimates of broccoli crop damage costs, the costs presented are only based upon the influence of weather and climate. There are no mechanisms provided by which the crucifer flea beetles are introduced into the area but rather just a measure of the damage they may cause by being present; the exogenous probabilities. The main use of Brody's spatially explicit damage function for this thesis will be to use the risk probability maps in the agent-based model to determine whether or not the pest in an infected shipment will be able to establish and spread if the pest is not discovered in the border inspection process. By incorporating the spatial damage function into the agent-based model, we will be able to determine the broccoli damage costs not merely as a result of weather and climate effects but also how damage to the broccoli crops are influenced by importer and inspector behavior.

Chapter 4: Methodology

This chapter provides an overview of the methodology used in this thesis and justifies its use. It examines the components, use, design elements and issues as well as the advantages and challenges of agent-based modelling (ABM). Examples of the prior use of agent-based models from various disciplines are also included.

In addition to the earlier definition given, agent-based modelling can also be considered a system which "is model[l]ed as a collection of autonomous decision-making entities called agents [where] each agent individually assesses its situation and makes decisions on the basis of a set of rules" (Bonabeau 2002, 7280). It is constructed using three main building blocks; agents (also referred to as actors), actions and routines, and decision making and evaluations (Pyka and Grebel 2006). It is important to note that agent-based models "do not necessarily include only parameters estimated from actual empirical data, but [they] may include parameters that are relevant for a specific theoretical meaning" (Billari et al. 2006, 8). Rather than looking to predict behavior, agent-based models emphasize the explanation of theories (but do not prove theorems) (Billari et al. 2006) and aid intuition (Axelrod 1997). While an agent-based model uses simulation techniques, its goal isn't to "provide an accurate representation of a particular empirical application" but rather to strengthen "understanding of fundamental processes that may appear in a variety of applications" (Billari et al. 2006, 9). Essentially, in their most basic form, an agent-based model "consists of a system of agents and the relationships between them" (Bonabeau 2002, 7280).

4.1 Components of an Agent-Based Model

Agents are the driving force in an agent-based model. Models may be created using one agent (or type of agent) or several agents depending on the phenomenon being explored. Agents should be autonomous; that is they can control their own actions; be reactive; responsive to their environment; proactive; can take initiative, adapt and have goal orientated behavior as well as have social ability and can interact with one another (Pyka and Grebel 2006). Their behavior may "be simple or complex, deterministic or stochastic, fixed or adaptive" (Billari et al. 2006, 3). Agents "may be capable of evolving, allowing unanticipated behaviors to emerge" (Bonabeau 2002, 7280) but should be kept as simple as possible to suit their application (Billari et al. 2006).

Adaptive agents have the ability to learn and change in response to their surroundings based upon their objectives and evolve by acting, evaluating and updating their objectives or actions (Billari et al. 2006). Agents may be classified into groups according to the actions they take (Pyka and Grebel 2006). The given actions of agents are governed by the routines and the routine's rules; how they are related to one another and how they interact with one another (Pyka and Grebel 2006). It is the differences in the agents' routines that contribute to the heterogeneity in the model (Pyka and Grebel 2006). Decision making and evaluation refers to the ability of the agents to choose how they are going to proceed in the model and how they adapt to their environment through the comparison of their expectations and objectives with the results of their actions (Billari et al. 2006).

4.2 Using and Designing an Agent-Based Model

Agent-based models are best used to model heterogeneous agents with heterogeneous interactions where the agents have the ability to learn and adapt. They are also beneficial to use in cases where the interaction between the agent and other agents can result in the alteration of the agent (Bonabeau 2002). While agents and their behaviors drive the need for an agent-based model, the environment in which they interact can also necessitate their use.

Agent-based models are particularly useful when the conditions of the model set the stage for the potential of emergent properties (Bonabeau 2002). Emergent properties can potentially arise when "individual behavior is nonlinear and can be characterized by thresholds, if-then rules or nonlinear coupling," when "individual behavior exhibits memory, path-dependence and hysteresis, non-markovian behavior, or temporal correlations including learning and adaptation," when "agent interactions are heterogeneous and can generate network effects" or when averages will not work (Bonabeau 2002, 7280-7281).

Other conditions in which agent-based models are useful include when there are issues with complexity, stochasticity and behavioral explanation. If the appropriate description or complexity is unknown, agent-based models provide the flexibility to incorporate more information as it becomes available through the updating of agents (Bonabeau 2002). Agent-based models are able to incorporate more complexity in the behavior of agents and can be used when individuals' behaviors cannot be explained through aggregate transition rates and/or when there is stochasticity in the agent's behavior (Bonabeau 2002).

When creating an agent-based model, there are several design issues to consider. Three major decisions to be made when creating an agent-based model should include the decision between using a specific or general model, the cognitive abilities and architecture of the agents and the model's level of abstraction (Doran 2006). The desired outcome of the modelling exercise will determine whether or not it is necessary to use a specific or general form of the model. A general model will provide the essentials of the situation and "discover properties that a real world situation has as a result of its structure and dynamics" whereas, despite requiring more detailed observations, specific models will predict likely outcomes of specific actions and provide specific insights and predictions (Doran 2006, 216).

Regardless of whether the model is general or specific, in order to be an agent-based model, there must of course be agents. Doran (2006) describes this as a two-staged process; the first of which is to decide on which agents will be represented from the real world and the second is to decide how this will be translated within the model. The cognitive and makeup of the agents will depend on what the agents are required to do, how much information and knowledge an agent is initially given and whether or not the agents will be able to learn and react within the model and to what degree (Doran 2006). The level of abstraction, aggregation or detail included in an agent-based model is partly determined by the selection of agents that are to be included in the model. According to Doran (2006), there are two main principles to follow when considering how much detail is to be included: "the model must be sufficiently detailed that it can address the questions to be answered [and] assumptions based on pre-conceptions are to be avoided" (page 217). Billari et al. (2006) suggests that real-world observation of actors and stakeholders can be used to help select the strategies and decision rules used in an agent-based model.

4.3 Advantages and Challenges of Agent-Based Modelling

According to Bonabeau (2002), there are three advantages that agent-based modelling has over other modelling techniques. The first advantage is that they capture "emergent phenomena...from the bottom up when the simulation is run" (Bonabeau 2002, 7280). Agent-based models show "how collective phenomena came about and how the interaction of the autonomous and heterogeneous agents leads to the genesis of these phenomena" (Pyka and Grebel 2006, 24). These phenomena arise from the interactions between agents in such a way that the whole of the system is greater than the sum of the individual parts (Bonabeau 2002). The second advantage of agent-based modelling is that it can provide a natural description of a system – it can model scenarios more realistically. Agent-based models can look at a system from within. The final advantage offered by Bonabeau (2002) is that this type of modelling is flexible; it allows for ease in changing "the complexity of the agents: behavior, degree of rationality, ability to learn and evolve, and the rules of interactions" as well as flexibility in changing the "levels of description and aggregation" and exploration of various institutional arrangements and potential development paths (page 7281). Billari et al. (2006) also point out addition advantages to using agent-based models including their ability to examine interactions between multiple agents, form complex social patterns and offer “a wide field of experimental games for educational and research purposes as well as for decision support and policy advice” (page3).

While agent-based modelling does have strengths and advantages over other types of modelling, it is also worth noting that they are not without challenges. Agent-based models can be time consuming to build and may be computationally intensive to run. In order to create a model that is in line with the goals of the research, it is important to determine at what level and specification to build the model to – what is the appropriate level of detail to include? A researcher can spend many hours over-specifying the model or not build the model up to a level that produces meaningful results. Bonabeau (2002) argues that in order for the model to serve its purpose, it must be built to the correct specifications with the appropriate amount of detail. This sentiment is echoed by Doran (2006) who suggests that “perhaps the central issue is just what potential properties of the model can reliably and completely be observed in the real-world scenario” (page 217). Billari et al. (2006) suggest that the key challenges in agent-based modelling are to find “a conceptual framework to structure the diverse field of ABMs, to calibrate the models with data and to integrate ABMs into real-world applications” (page 3).

Parameterization can present a major problem in agent-based modelling of real systems. Results can be uncertain and lack the reliability to provide adequate predictions and meaning when parameters are uncertain or unknown which is commonplace in many models (Grimm and Railsback) although this does not have to be the case. According to Wiegand et al. (2004), parameter values need not be as important as long as the model is structured realistically so that it captures the main structures and processes. This will provide observed patterns which can in turn, be used to reduce the uncertainty of the parameters and can provide indirect parameter estimation (Wiegand et al. 2004).

4.4 Examples of Agent-Based Models

Agent-based models have been used in a wide variety of disciplines to model a variety of different systems. In business, they have been used to model flows such as evacuation routes, traffic, customer behavior in stores, markets such as the stock market or auctions, organizations or diffusion and adoption of innovation (Bonabeau 2002). They have been used in population and demography to examine such things as assortative mating and its role in population growth (Murphy 2006), age-at-marriage norms (Diaz and Fent 2006) and the effects of education on obesity rates among women (Burke and Heiland 2006). Ecology has been using individual-based models (IBM) for quite some (see Grimm 1999) and in recent years the approach of IBMs has been merging with those of agent-based models; that is that IBMs have been slower than agent-based models in terms of adaptive behavior but are beginning to learn from them (Grimm and Railsback 2006). Ecology has used individual-based modelling and now, agent-based modelling to examine adaptive forest management (Gebetsroither et al. 2006) and biological evolution (Conte et al. 2006). Economics has used agent-based models for applications such as management of resource use (Boxall et al. 2005) as well as the design of electricity markets and restructuring (Bunn and Olivera 2001, Nicolaisen et al. 2001). While this type of modelling has been used in investigations of the spread of invasive species previously (e.g., Bass and Chan 2004; Cole and Albrecht 1999), this thesis will be apparently the first to use an agent-based modelling framework to analyze importer and border enforcement strategies for invasive species management.

Chapter 5: A Spatially Explicit Agent-Based Model

This chapter discusses the development and structure of the agent-based model including a discussion of the software used to create it. It outlines the abilities and decision making functions of the agents and examines the ways in which the theoretical model presented by Ameden, Cash and Zilberman and the spatial explicit damage function by Brody play into its construction and outcomes.

In order to create this agent-based model of border enforcement for invasive species management, several design issues needed to be settled including the choice of software in which to model, the structure and ordering of the events occurring in the model as well as the level of detail to be included in the model construction.

5. 1 NetLogo

The agent-based model developed for this thesis was created using NetLogo. NetLogo provides a programmable modelling environment which can be used to simulate both natural and social phenomenon (NetLogo User Manual 2007). It was authored by Uri Wilensky in 1999, written in Java and is continually being developed and updated at the Center for Connected Learning and Computer–Based Modelling at Northwestern University (NetLogo User Manual 2007). While the model in this thesis was created using NetLogo version 3.1.5, newer versions have since been released (most recently version 4.0.3).

NetLogo was chosen as the software platform for this thesis for several reasons. Firstly, it has the ability to create multiple agents (up to and including thousands of agents) which can operate independently and is "well suited for modelling complex systems developing over time" (NetLogo User Manual 2007, 1). NetLogo contains many pre-written modelling examples that can be used to familiarize oneself with the programming language and/or modified to suit the programmer's needs. Another benefit of NetLogo is its BehaviorSpace feature which allows the user to test the model and collect data from multiple runs of a model specification. Essentially, NetLogo was chosen for the creation of this agent-based model because it had the ability to model the spatially explicit damage function as well as incorporate the theoretical economic modelling in such a way that allowed for both numerical output as well as a detailed, strong visual representation of the model (refer to Figure 5-1 below for illustration). The main concern that arose from working in NetLogo was the length of time it took to collect the data from multiple runs of some of the model specifications.

5.2 Model Structure

In this agent-based model there are three types of agents: importers, border enforcement agents (inspectors) and the crucifer flea beetles. While the importers and the inspectors have the ability to make their own decisions based on their goals and objectives, the crucifer flea beetles will only have the ability to react to their surroundings. The purpose of this model is to examine the effects of importer and inspector behavior on managing invasive species risk at border crossings. It examines the conditions under which importers will choose higher pretreatment levels for their cargo and the factors influencing a firm's port selection. The model also explores the influence of increased inspections, increased success rate of an inspection and what happens when the inspectors choose to destroy infected shipments that are discovered rather than treat them at the border. Ultimately, this model will show the conditions under which the invasive species risk will be reduced and the effect this will have on agricultural losses.

5.2.1 Crucifer Flea Beetles

The crucifer flea beetles have assigned behaviors only. They have no control over whether or not they are present in a shipment, whether or not they survive pretreatment efforts by the importers or where they are released if they survive through the border inspection process. The beetles are able to identify whether or not they have been released in area that contains broccoli crops and have potential to spread to other adjacent broccoli crops but their ability to establish in the area is determined by the establishment probability maps created by Brody.

5.2.2 Importers

Individual importers have the ability to choose both their level of pretreatment efforts as well as the port destination of their shipment. They do not have control over the initial infection rate of a shipment nor do they know whether or not their shipment is initially infected. Each importer is assigned a probability that their shipments contain an infection. For each period, there is a random draw from a uniform distribution. If the assigned probability of infection is greater than or equal to that of the random draw, the shipment will be considered infected for that period. If the assigned probability is less than that value of the draw, the shipment is not infected in that period.

Mathematically:

b_i is the chosen value for importer i $(0 \le b_i \le 100)$
α_b is the value drawn from the uniform distribution to determine the presence of an infection $(0 \le \alpha_b \le 100)$

if $b_i \ge \alpha_b$ then the shipment is assumed to be infected, pests are present ($b_i = 1$)
if $b_i < \alpha_b$ then the shipment is assumed not infected, pests are not present ($b_i = 0$)

Before their shipment is sent, importers will be able to decide if they want to engage in pretreatment efforts or not. If an importer chooses not to engage in pretreatment efforts, they risk sending an infected shipment to the port based on the value of b_i. If an importer chooses to participate in pretreatment efforts, the success of their efforts depends upon the level of pretreatment they select and its associated probability of success. The effectiveness of the pretreatment is based upon both an internal rate of pretreatment success (that is, higher levels of pretreatment are more effective than lower levels of pretreatment) as well as an external rate of success that can be set to various levels of effectiveness in order to see how firms make tradeoffs in choosing which level of pretreatment to use. For each period, the success of a firm's pretreatment efforts is calculated as follows. First, values are assigned to represent the base effectiveness for the each potential choice of pretreatment effort level. This value is then multiplied by the value of the pretreatment effort level to calculate the probability of successful pretreatment. For example, a 25 percent effectiveness rate (the external rate) for level one pretreatment choice (internal rate) will not be as effective as a level three pretreatment choice with a 25 percent effectiveness rate. Once the probability of successful pretreatment is calculated, there is then a draw from a uniform distribution. If the calculated probability is greater than or equal to that of the draw, the pretreatment will be assumed to have been successful (there are no pests in the shipment) otherwise it will be assumed to have failed. Mathematically:

$$p_i^l = \lambda_l m_l$$

where: p_i^l is the probability of success for pretreatment effort level l for firm i
λ_l is the base level of effectiveness of pretreatment level l
m_l is the scalar for choosing a higher pretreatment level

α_p is the value drawn from the uniform distribution to determine the success of pretreatment efforts $(0 \leq \alpha_b \leq 100)$

if $p_i^l \geq \alpha_p$ then the pretreatment was successful, no pests present ($p_i^l = 0$)
if $p_i^l < \alpha_p$ then the pretreatment was either not used or was unsuccessful ($p_i^l = 1$)

The goal of the importers is to minimize their costs which include pretreatment efforts, transportation costs, and their expected costs of fines and fees for being caught with an infected shipment by the inspector at the port they have chosen to ship through. In addition to being fined for an infected shipment, importers may also lose the value of their shipments if they are destroyed or be required to pay treatment costs at the port. In this model, it is assumed that the importers have perfect information regarding the actions of the port inspectors. The rates at which the inspectors inspect and their abilities to conduct a successful inspection at each port influence the decisions regarding pretreatment efforts and port selection made by the inspectors.

Mathematically:

$$E[c_i] = e_{il}k_l + t_{ij} + S_j[v_i(\gamma)Q_i + r(1-\gamma)Q_i + f]$$

where: $E[c_i]$ is the expected total cost of shipping for importer i ($)
e_{il} is the pretreatment effort level (l) by importer i
k_l is the cost of pretreatment effort level l ($)
t_{ij} is the transportation cost for importer i shipping to port j
S_j is the success rate of an inspection at port j [endogenous – see below]
v_i is the value of the shipment ($)
γ is the inspectors' decision to treat (γ=0) or destroy (γ=1) an infected shipment
r is the cost of treatment at the border ($)
Q_i is the quantity of the shipment
f is the fine for being caught with an infected shipment ($)

Importers will calculate their expected costs for each combination of pretreatment efforts and port choice in order to ensure that they make the selection that minimizes their costs.

5.2.3 Inspectors

At each of the ports, there will be one representative inspector who will determine whether or not to inspect a given shipment. Inspectors are given a base rate at which to inspect. Additionally, inspectors will also have the ability to identify importers with past inspection violations and will have the ability to inspect those importers at a higher rate. Inspectors will update their information based upon importers' behavior in prior periods for the current year and adjust their inspection rates accordingly. Importers with higher numbers of violations in past periods of the current year will have a greater chance of being inspected in the present period than those who have violated fewer times, those who have not violated or those importers who have never been caught with an infected shipment. Prior violations are set to zero at the beginning of each year.

Mathematically:

$$I_j = \rho_j + \theta_j \frac{n_i}{2}$$

where: I_j is the inspection rate at port j
ρ_j is the base rate of inspection ($0 \le \rho \le 100$)
θ_j is the additional rate of inspection for previous violators ($0 \le \theta \le 100$)
n_i is the number of times importer i was caught with an infected shipment in the current year

After the inspection rate is calculated, there is another random draw from a uniform distribution to determine whether or not the inspection would take place. If the calculated rate of inspection was higher than the value from the random draw, inspections took place otherwise they did not.

α_I is the value drawn from the uniform distribution to determine whether or not an inspection in carried out ($0 \le \alpha_I \le 100$)

if $I_j \ge \alpha_I$ then an inspection would take place ($I_j = 100$)
if $I_j < \alpha_I$ then an inspection would not occur ($I_j = 0$)

The success rate of an inspection; defined as detecting an infection when one is present in a shipment or accurately declaring a shipment clean; will be based on a base "ability" to search a shipment and will only be applied to those shipments which have been chosen to be inspected.

$$S_j = \beta_j I_j b_i p_i$$

where: S_j is the success rate of an inspection at port j

β_j is the base ability to conduct a successful inspection
I_j is the inspection rate at port j
b_i is whether or not the shipment was originally infected
($b_i = 1$ if infected, $b_i = 0$ if not infected)
p_i is whether or not the pretreatment effort by the importers was successful ($p_i = 1$ if unsuccessful, $p_i = 0$ if successful)

A final random draw from a uniform distribution is used to determine whether or not an inspection was carried out successfully. If the calculated success rate of inspection was higher the value of the random draw and an inspection took place, the inspection would be a success (a pest was found if one was present) otherwise there would not be a successful inspection

α_S is the value drawn from the uniform distribution to determine whether or not an inspection in carried out ($0 \leq \alpha_S \leq 100$)

if $S_j \geq \alpha_S$ then the inspection is successful ($S_j = 1$)
if $S_j < \alpha_S$ then an inspection would not occur ($S_j = 0$)

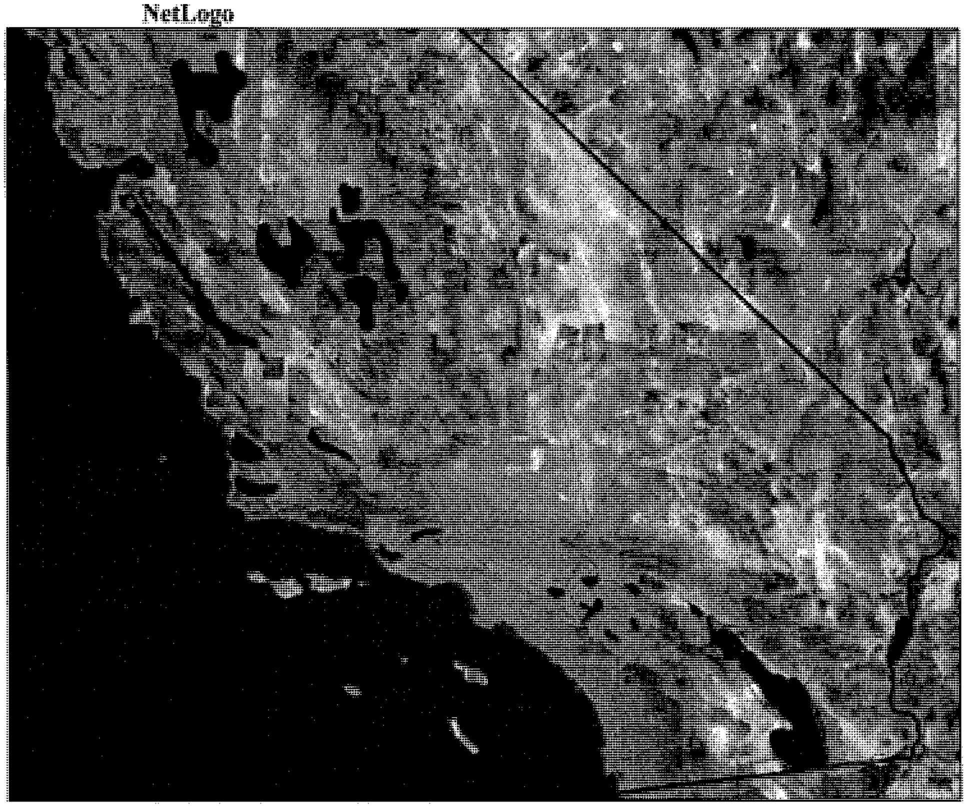
Whether or not an inspector chooses to treat or destroy an infected shipment if one is discovered will depend upon the damages that have already been done to the broccoli crops. This represents the inspectors' ability to assume an allowable loss of crop. There will be a threshold set whereby if the percentage of broccoli crop damage exceeds a chosen value, the inspectors will choose to destroy the infected shipment (which causes higher costs for the importers as they will lose the entire value of their shipment) rather than treat the infected shipment.

5.3 Model Construction

5.3.1 Spatial Components

Before beginning the economic components of the agent-based model, it was important to first ensure that the spatial elements of the model were set up correctly. First, an image of California was obtained from Google Earth (2007) and was overlaid with a map from the United States Department of Agriculture (USDA) which depicted the broccoli crop areas in California (2002). Then, the broccoli crops were marked on the Google Earth (2007) image using its polygon tool. Major roadways were drawn in to indicate the paths the shipments could take. The map of broccoli crops in California is shown in Figure 5-1 below.

Figure 5-1: Map of California Indicating Broccoli Crops and Major Roadways used in NetLogo

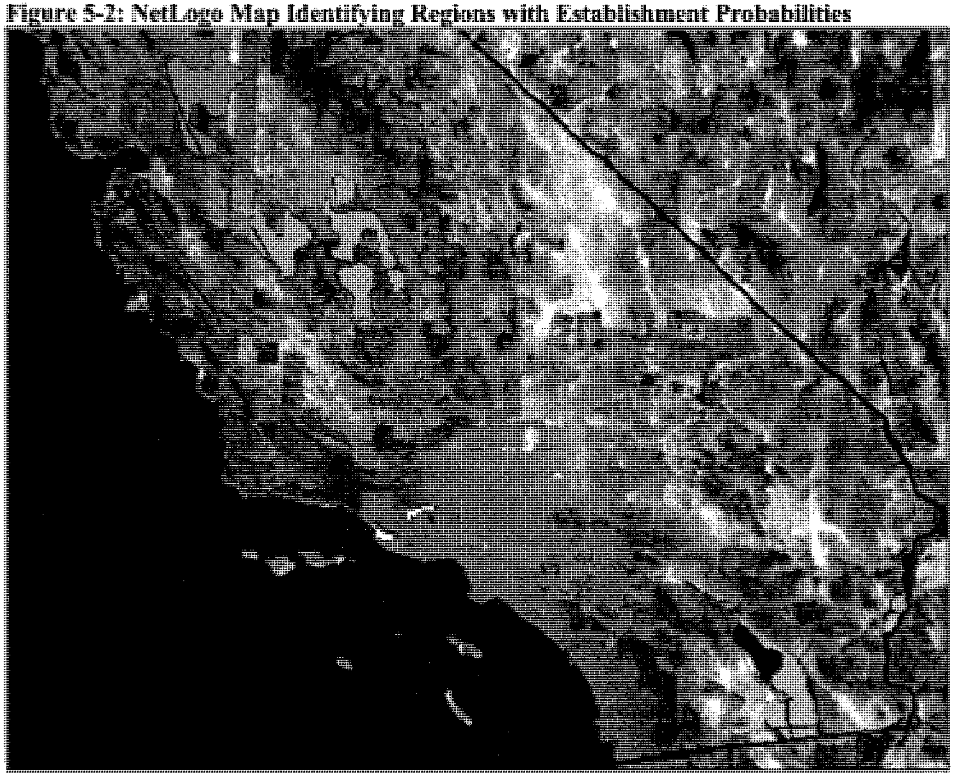


To import the map into NetLogo, it was necessary to match the size of the patches in NetLogo with the real world size and spacing. This was achieved by selecting two patches on the map in NetLogo and calculating the distance between them using their x and y coordinates and comparing this to the distance calculating using the same two locations on the map in Google Earth (2007).

From this information, the number of kilometers per patch per side was calculated and then squared to give the area per patch in km^2. To ensure that the four main broccoli growing regions (the Central Coast, the South coastal, the San Joaquin Valley and the South Eastern Desert counties) had the correct number of patches per region, the area was calculated from the patches and compared to the data provided by the Crop Profile for Broccoli in California (1999). In order to determine the amount of broccoli that should be contained within a patch, the real world broccoli area was divided by the area in NetLogo to provide a density measure based upon the patch's location; each of the four growing regions have different density values. The density was then multiplied by the average number of broccoli plants per km^2 to give the number of broccoli plants by patch. The model makes the assumption that the same amount of broccoli exists throughout the year; it does not account for harvesting rates. Once the map of Californian broccoli crops was completed, it was then possible to underlie this map with the spatially explicit damage function maps created by Brody.

To implement the spatially explicit damage functions created by Brody, patches were defined by region and assigned a specific colour to represent a given level of establishment probability. The probability of establishment was set to the highest level in the range of establishment probabilities. For example, if a region had a frequency of occurrence between 20 percent and 40 percent, the probability of establishment for that region would be set to 40 percent. If a crucifer flea beetle were initially able to arrive at a patch containing broccoli, the underlying colour code of that patch would determine the probability of the crucifer flea beetle to establish and spread from that patch. If the beetles are able to establish in an area, they will have the ability to spread out by moving to the patches adjacent to the patch they are on provided that the adjacent patch contains broccoli and dependent upon the establishment probability related to that patch given the time period. Initially, the beetles will start on a patch 1x1, then spread out to patches 3x3, then on to patches 5x5 and so forth until they can no longer find broccoli or are unable to establish. If a beetle does come into contact with a broccoli patch and is able to establish, it is assumed that the patch will be destroyed by the beetle and damages will occur. This is illustrated in the model by a change in the colour of the broccoli crops if damages occur (using the map shown in Figure 5-1). Just as the probabilities in Brody's model were calculated in two week increments, the model updates the underlying establishment probability every two weeks. An example of the underlying establishment probability in the map is illustrated in Figure 5-2 below.

Figure 5-2: NetLogo Map Identifying Regions with Establishment Probabilities



After the spatial elements were constructed in the model, the focus was shifted on to incorporating the economic components.

5.3.2 Economic Components

In order to begin modelling the economic components, it was first necessary to identify and define the variables that were included in the model so that they could be read in NetLogo. These variables included such elements as crop information, time, as well as firm and inspection information. The parameters of the variables included in the model, along with their counterparts from the mathematical equations, are seen in Table 5-1 below. Once the variables were defined, the equations for both the importers and inspectors were constructed as outlined in sections 5.2.2 and 5.2.3.

Table 5-1: Variables and Parameters of the Agent-Based Model

Equation Variable	NetLogo Variable Name	Description	Range of Values
b_i	*i*_infection_rate	the chosen infection value for importer i	0 – 100%
λ_l	pretreatment_effectiveness*l*	base level of effectiveness of pretreatment level l	0 – 100%
e_{il}	choice_*i*	pretreatment effort level (l) chosen by importer i	0, 1, 2, 3
m_l	choice_*il*	scaler for choosing a higher pretreatment level	*l*=0; 0 *l*=1; 0.4 *l*=2; 0.65 *l*=3; 1.0
k_l	pre_cost*l*	cost of pretreatment effort level l ($)	$0 – 100
t_{ij}	trans_cost_*i*_*j*	transportation cost for importer i shipping to port j	$0 – 100
v_i	value_*i*	the value of the shipment ($) for firm i	$0 – 1000
Q_i	shipment_Q_*i*	quantity of the shipment for firm i	0 – 100
r	border_treatment_cost	cost of treatment at the border ($)	$0 – 100
f	fine	fine for being caught with an infected shipment	$0 – 1000
ρ	base_rate_of_in_port*j*	base rate of inspection at port j	0 – 100%
θ	additional_violation_port*j*	additional rate of inspection for previous violators	0 – 100%
β	in_base_s_rate_port*j*	base ability to conduct a successful inspection	0 – 1.0
	destroy_threshold	if damage to crops is greater than the threshold, inspectors choose to destroy rather than treat	0 – 100%
	establishment_modifier	ability to change establishment probabilities	-100 – 100%
	pest_per_truck	number of pests in an infected shipment	0 – 100
	timesteps_per_week	number of shipments per week	0 – 100

Three different importers were created so that it was possible to compare the reactions of firms with different infection rates and transportation costs. For each importer, eight cost equations were constructed; one for each combination of port selection (Calexico-port one or Otay Mesa-port two) and pretreatment choice (no treatment, level one, level two or level three); for a total of 24 cost equations.

Inspection rate calculations were constructed for each port and each importer (to capture the effects of potential repeat offenders) while the success rate of inspection (i.e. finding an infected shipment when one is presented) calculations were constructed for not only each port and importer but also for each potential level of pretreatment as each level of pretreatment effort by importers would have an associated rate of success of eliminating a pest if one was originally present.

Once the equations were developed and tested to ensure their accuracy (importers choosing the combination of port and pretreatment that minimized their costs given their expectations about being successfully inspected at the chosen port and inspectors were inspecting and successfully inspecting based on the value of the random draw from the uniform distribution), it was then possible to use the BehaviorSpace feature in NetLogo to test the effects of the different parameters in the model. The BehaviorSpace feature allows the model to be run a given number of times with different model specifications which allows for examination of the effect of inspector behavior on firms' pretreatment and port choices, the conditions under which importers' decisions change and the effect their interactions have on the damages caused to the broccoli crops.

In order to test the model, it was initially run using firms that were homogenous with respect to their infection rates, transportation costs, shipment quantity and values. This provided the opportunity to ensure that the model was running correctly and provide an idea of how much of variation was due to the underlying probability of establishment and the random draws. The results of the homogeneous importers will help to determine whether or not the variation in behavior of heterogeneous importers is due to external or internal forces and what impact the variety of importer types has on invasive species risk. The results from homogeneous importers will provide a base case to which the results from heterogeneous importers can be compared as well as provide a calibration tool for the heterogeneous firms. The results of the modelling are presented and discussed in Chapter Six.

Chapter 6: Analysis and Results

This chapter presents the results of the agent-based model developed in Chapter Five. Specifically, it examines the effect of changing model parameters on importers' pretreatment and port choices and the effects this has on in crucifer flea beetle damage to Californian broccoli crops. The model identifies the conditions under which importers choose higher pretreatment levels and whether or not they make tradeoffs between and among pretreatment efforts and port selection. The model demonstrates the conditions under which the invasive species risk is greatest and reports the potential damages that may arise from their introduction.

For each model specification, the average of 100 iterations was calculated at each level of the parameter being tested; usually in quartiles. Each iteration of the model represents a one year run. Results of the model show the percentage of times out of the 100 runs that a given firm chooses to send their shipment to each port as well as the frequency in the 100 runs that a firm chooses each level of pretreatment. The model also reports the number of times a firm has been caught with an infected shipment and the average amount of damage to the broccoli crops that accrued over the run.

After first testing the model with homogeneous firms, the model was adjusted to add in heterogeneity among the importers. The importers differ in terms of their infection rates (one high, one medium and one low) and their transportation costs in order to determine whether or not different types of firms respond differently to the inspectors' actions and the potential effects this may have on pretreatment choices and invasive species risk. Model specification were run to examine the effects of inspector behavior such as inspection and success of inspection rates, the treat or destroy decision and fine selection as well as effects of non-inspector decisions such as pretreatment costs to determine the conditions under which the invasive species risk is lowest.

For the heterogeneous model runs, parameters and variables that were not being tested in the model specified were held constant at the values presented in Table 6-1 below unless otherwise specified.

Table 6-1: Variables and Parameter Values for Heterogeneous Importers

NetLogo Variable	Value
a_infection_rate	100%
b_infection_rate	55%
c_infection_rate	10%
trans_cost_a_1, trans_cost_a_2	$100, $25
trans_cost_b_1, trans_cost_b_2	$50, $50
trans_cost_c_1, trans_cost_c_2	$25, $100
value_a, value_b, value_c	$500
shipment_Q_a, shipment_Q_b, shipment_Q_c	100
precost_1, precost_2, precost_3	$25
pretreatment_effectiveness1, pretreatment_effectiveness2, pretreatment_effectiveness3	100%
base_rate_of_in_port1, base_rate_of_in_port2	100%
additional_violation_port1, additional_violation_port1	100%
in_base_s_rate_port1, in_base_s_rate_port1	1.0
destroy_threshold	100%
fine	$1000
border_treatment_cost	$25
pest_per_truck	2
establishment_modifier	0
timesteps_per_week	2

6.1 Effects of Inspector Behavior

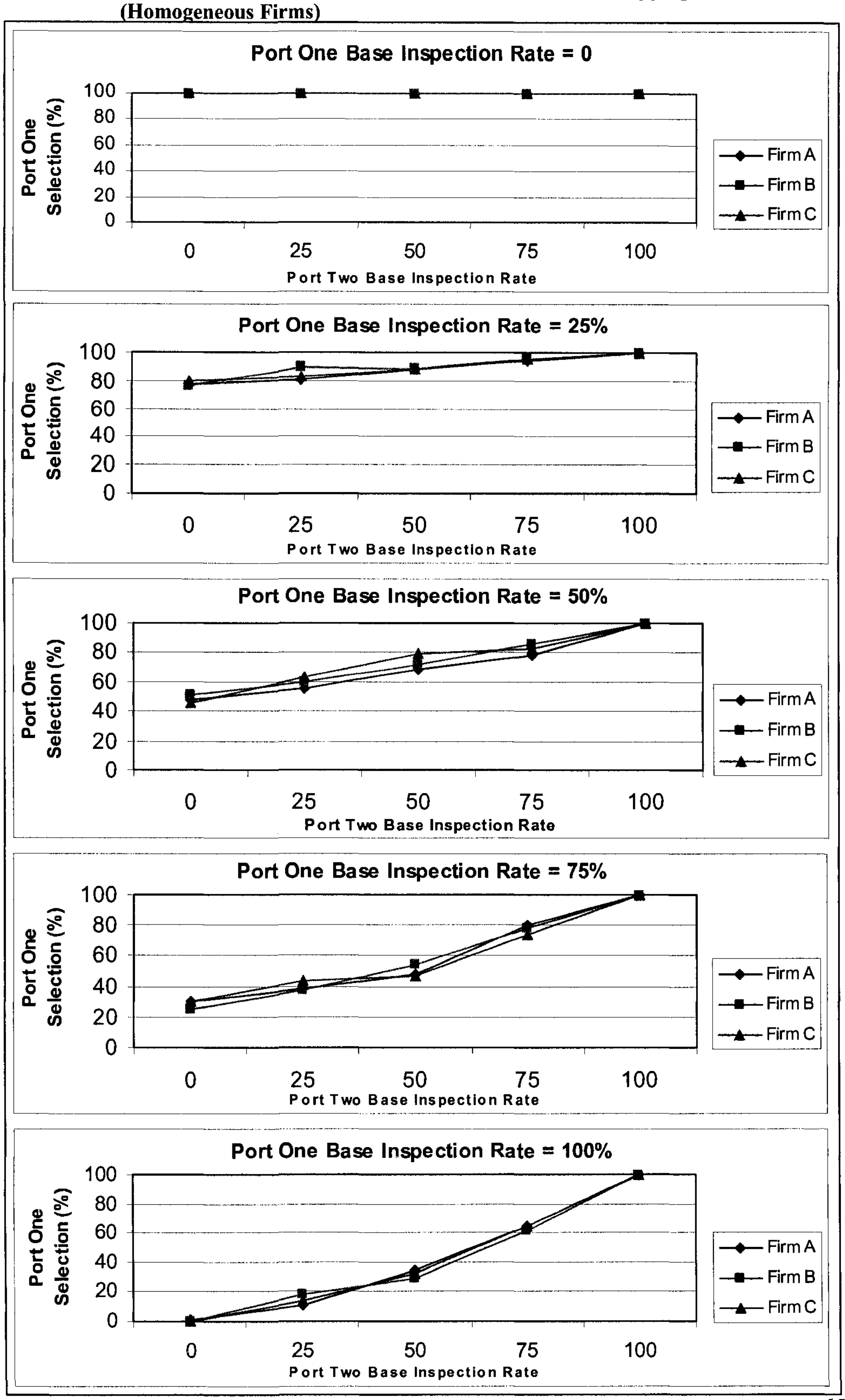
The abilities of the port inspectors play one of the largest roles in reducing invasive species risk. Firms use their expectations about inspector behavior when making decisions about their pretreatment choices. The inspectors have the ability to inspect a given percentage of shipments, the potential to conduct successful inspections, choose whether to treat or destroy discovered infected treatments and can charge a fee for treatment at the border if necessary, as well as administer fines for violations. While inspectors do not know the infection rate for a given importer (b_i), they are able to identify importers with previous violations (n_i) and can adjust their inspection rates accordingly (θ_j). Ports can have the ability to differ from one another in their abilities to conduct an inspection (ρ_j) as well as being able to conduct a successful inspection (β_j) depending upon the model specification selected. The effects of changes in inspector behavior are described below.

6.1.1 Base Inspection Rates and Base Success Rates of Inspection

Port inspections are essential to reducing or eliminating invasive species risk. Without inspections or the perceptions of inspections, importers lose the incentive to ensure that their shipments are pest-free. Importers will not invest money in pretreatment efforts if there are not potential benefits such balancing the cost of pretreatment with saving money on violation fines. In this model specification, the base rate of inspection (ρ_j) was increased in quartiles from 0 to 100 percent at both port one and port two while the base ability to conduct a successful inspection (β_j) was held at 1.0. The results show the influence of the base inspection rates when they are consistent between the two ports as well as what happens when they differ.

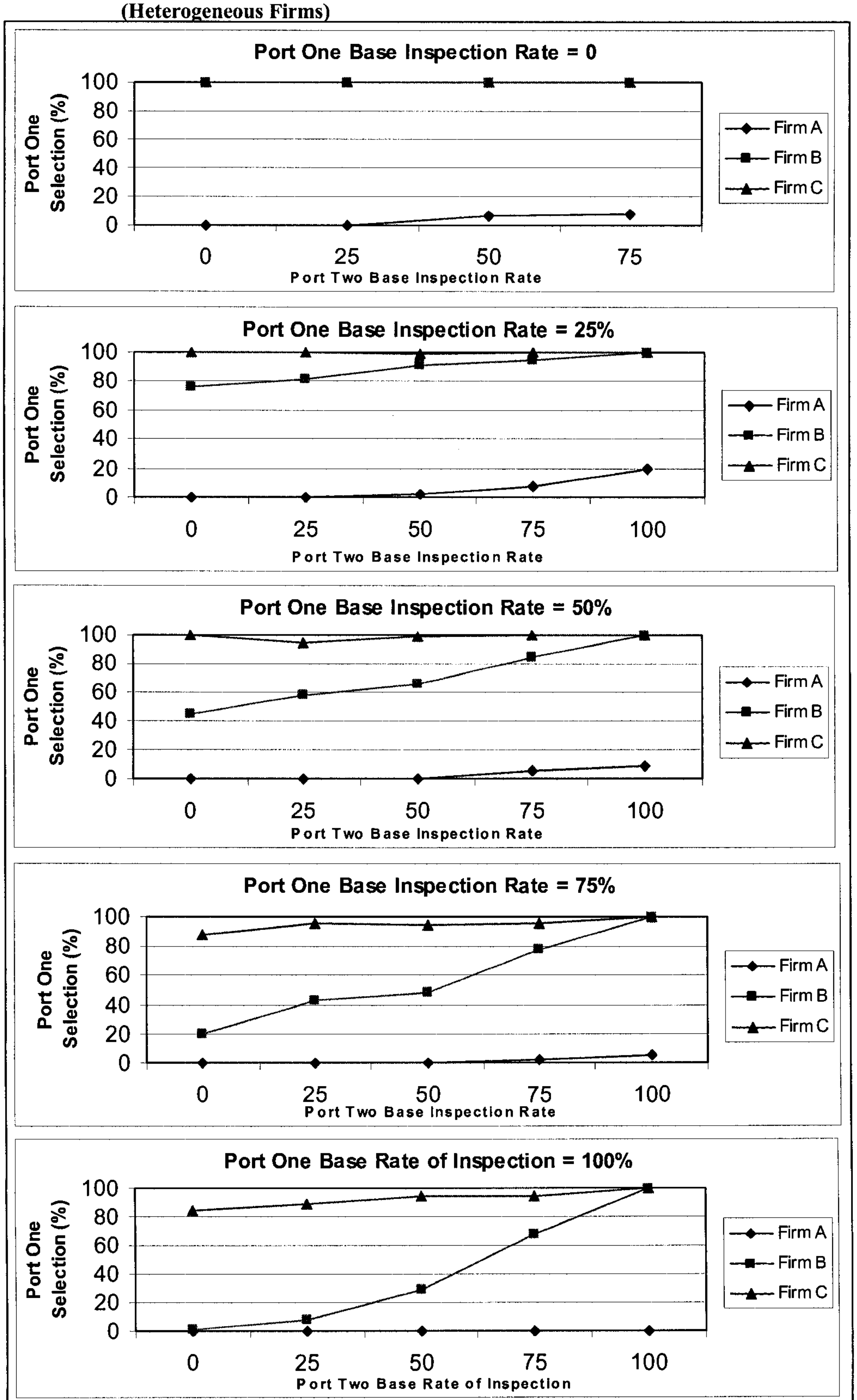
The results from the homogeneous importers showed that base inspection rates have a large effect on the importers' behavior. When using homogenous firms in the model, firms had identical transportation costs to each port. When the ports differed in their inspection rates and the costs of transportation are the same for both ports, the largest change in importer port selection occurs when the one port is not inspecting at all. As the inspection rate at port one increases while the rates at port two remain low, the firms will begin to ship more through port two until the point where the ports have equal inspection rates or the inspection rate at one port rises above the inspection rate at the other as seen in Figure 6-1. Variation among the firms can be attributed to the random draws from the uniform distributions that play a role in determining whether or not the inspections take place.

Figure 6-1: Base Rates of Inspection by Port and the Frequency of Shipping to Port One (Homogeneous Firms)



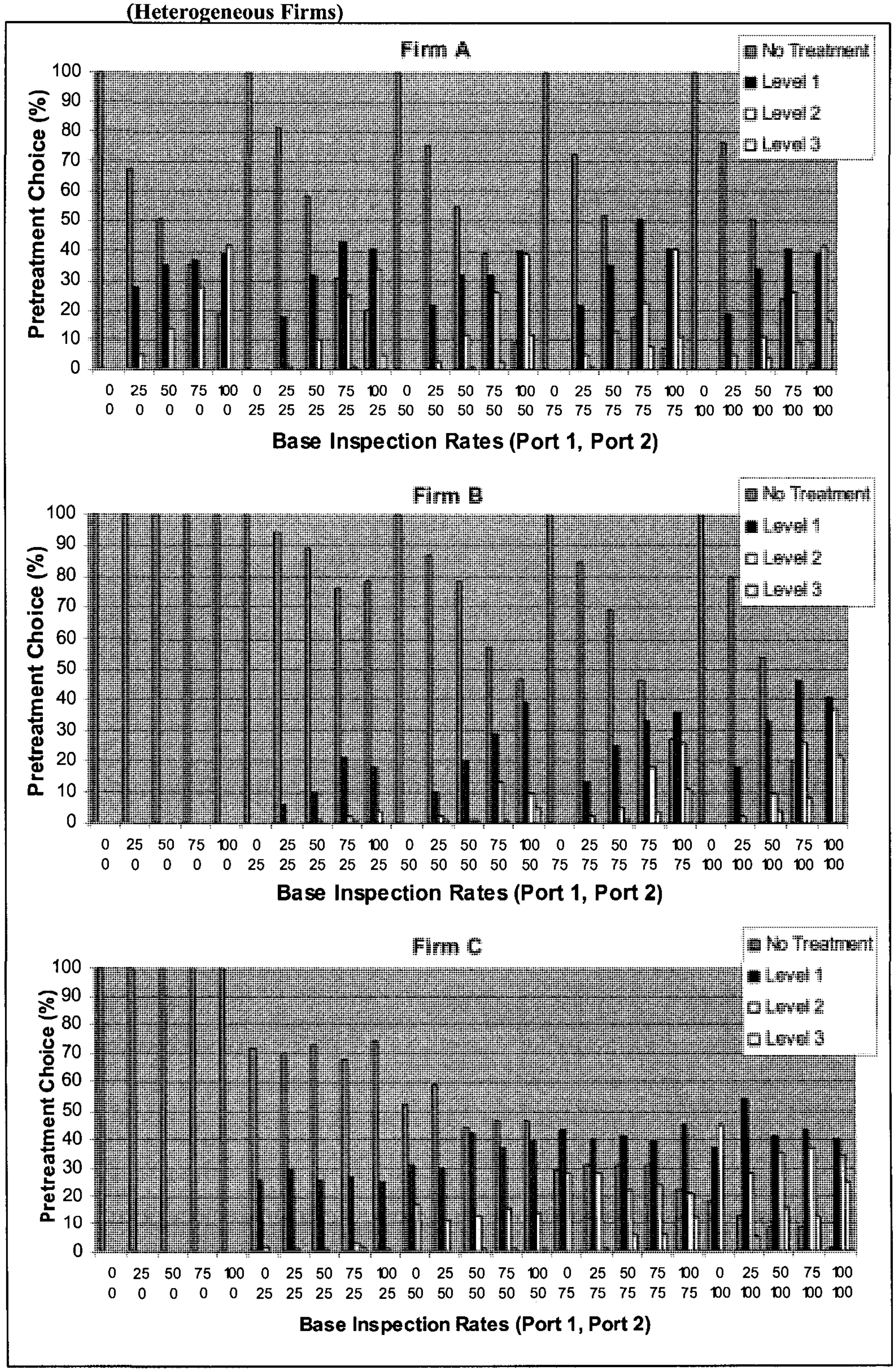
The results on the effects of changing the base rate of inspections on heterogeneous firms are not as straightforward as those in the case of homogenous firms. When firms have varying transportation costs among ports, this can have a large effect on which port they choose to ship through, regardless of the base inspection rate. If the costs of shipping to a port with a higher base inspection rate, including the cost of needing increased pretreatment, are lower than the costs of shipping to a port with a lower base rate of inspection, the firm will choose to ship to the port with the higher base rate of inspection. Firms tend to ship to the port that has lower transportation costs for them even if it means they are required to engage in more pretreatment efforts. If a firm is willing to send their shipments through a port that results in higher transportation costs for them, this could be potentially be seen as a signal to that port that their inspection rates are too low and there may be an increased risk of a firm crossing with an infected shipment. If the firm has transportation costs that are equal for both ports, then they will chose to ship to the port with the lower base rate of inspection. These results are shown in Figure 6-2.

Figure 6-2: Base Rates of Inspection by Port and the Frequency of Shipping to Port One (Heterogeneous Firms)



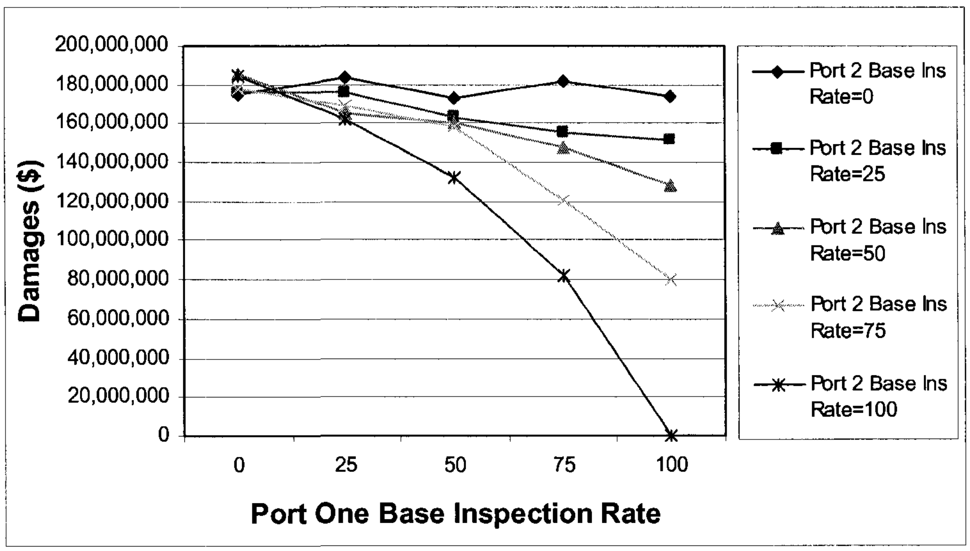
Pretreatment efforts increase in their frequency of use as well as the level of pretreatment used as the base rate of inspections increases at the port to which a firm prefers to send its shipments. This is demonstrated in Figure 6-3.

Figure 6-3: Base Rates of Inspection by Port and the Frequency of Pretreatment Choice (Heterogeneous Firms)



Overall, as inspection rates at the ports increase, firms are choosing to engage in higher pretreatment efforts. This indicates that as inspection rates increase, overall damages to broccoli crops should decline as the number of shipments sent to the ports without pretreatment declines. Does the variety of importer types play a role in either increasing or decreasing the overall damage? When the model was run using homogeneous firms, the greatest amount of damage is created when either one port is not inspecting at all or when there are large discrepancies between the inspection rates at the two firms as seen in Figure 6-4.

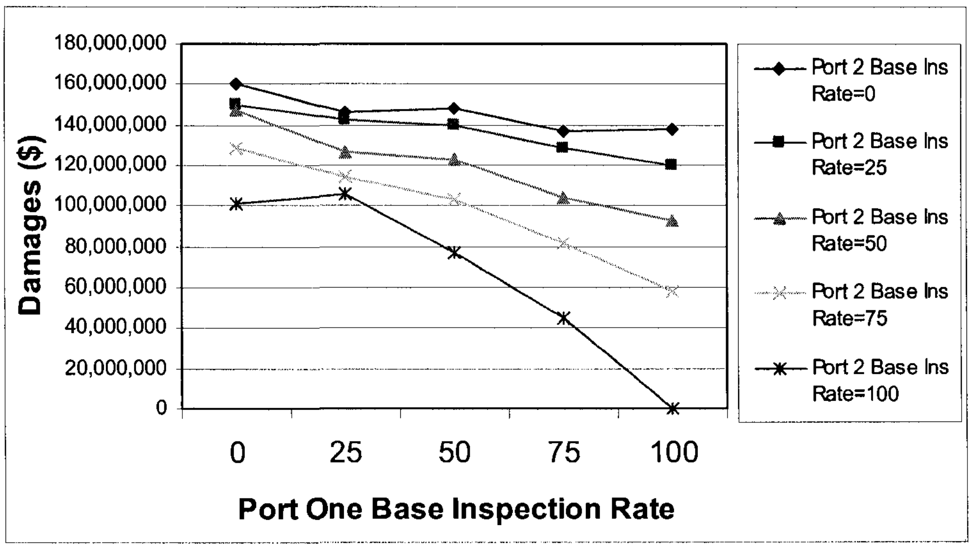
Figure 6-4: Base Rates of Inspection by Port and Broccoli Crop Damage (Homogeneous Firms)



As the difference between the inspection rates between the two firms are decreased (that is, the firms are inspecting at similar rates) and as the rate of inspection increases, the damage caused to the broccoli crops falls.

The results that arise once the heterogeneity is added in the firms show a different picture as illustrated in Figure 6-5. Under this scenario, there are lower damages to broccoli crops when the base rate of inspections is higher at port two. This is due to the fact that the firm with the highest infection rate (Firm A) has a preference for shipping to port two even if it means engaging in higher levels of pretreatment efforts. Overall, the damages to broccoli crops are lower in the scenario with heterogeneous firms than that with the homogeneous firms likely due to the fact that some of the heterogeneous importers have lower infection rates than the homogeneous importers and the fact that heterogeneous firms are more responsive with their pretreatment efforts as rates change at their preferred port.

Figure 6-5: Base Rates of Inspection by Port and Broccoli Crop Damage (Heterogeneous Firms)



Inspection rates are important in reducing invasive species risk but without the ability to conduct a successful inspection, they might as well not even take place. A successful inspection is defined as one where, if an infected shipment is presented for inspection, the infection will be discovered by the inspector. In this model specification, the base ability to conduct a successful inspection (β_j) was increased in quartiles from 0 to 1.0 at both ports while the base rate of inspection (ρ_j) was held constant at both ports at 100 percent ensuring that an inspection would take place.

The results of increasing the base success rates of inspection for the homogeneous firms are similar to the results of increasing the base rate of inspection. As the base success rate of inspection is increasing at one port with the other port being held steady, firms' engage in higher pretreatment effort. Pretreatment efforts are highest when ports have a high base success rate of inspections and are similar to one another in their rates.

The results found when examining the effects of a changing base success rate of inspection for the heterogeneous firms was also similar to those found when examining the base rate of inspections. Increasing the base success rate at the port which the firm prefers to ship to will lead to an increase in pretreatment efforts. By keeping the rates similar between ports, inspectors will be able to increase the pretreatment efforts of all the firms. However, if the success rate of inspection is only increased at one port, this may not reduce the invasive species risk overall. This is in line with the result found by Ameden, Cash and Zilberman (2007) and is illustrated in Figure 6-6 and Figure 6-7 below.

Figure 6-6: Base Success Rates of Inspection by Port and the Frequency of Shipping to Port One (Heterogeneous Firms)

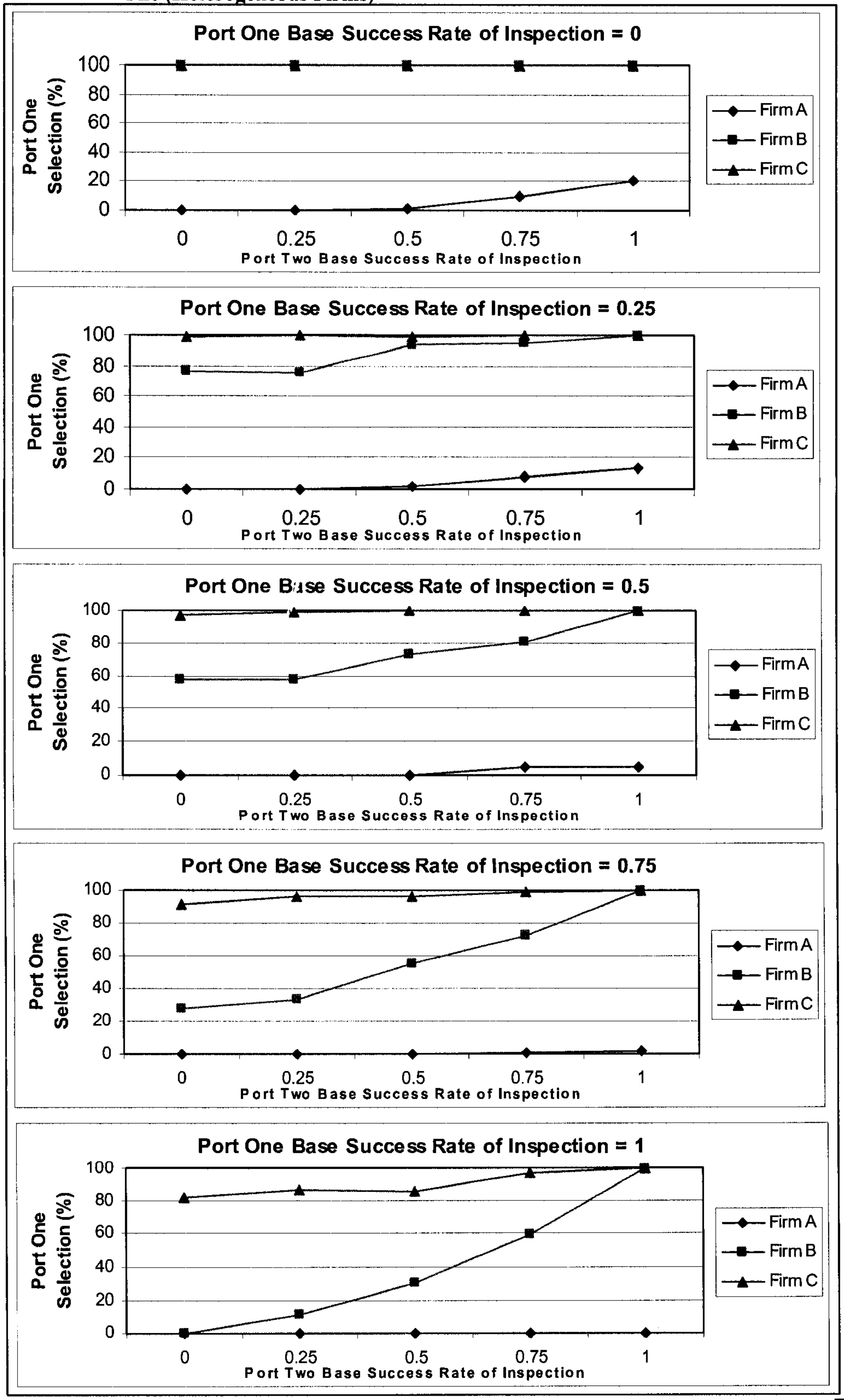
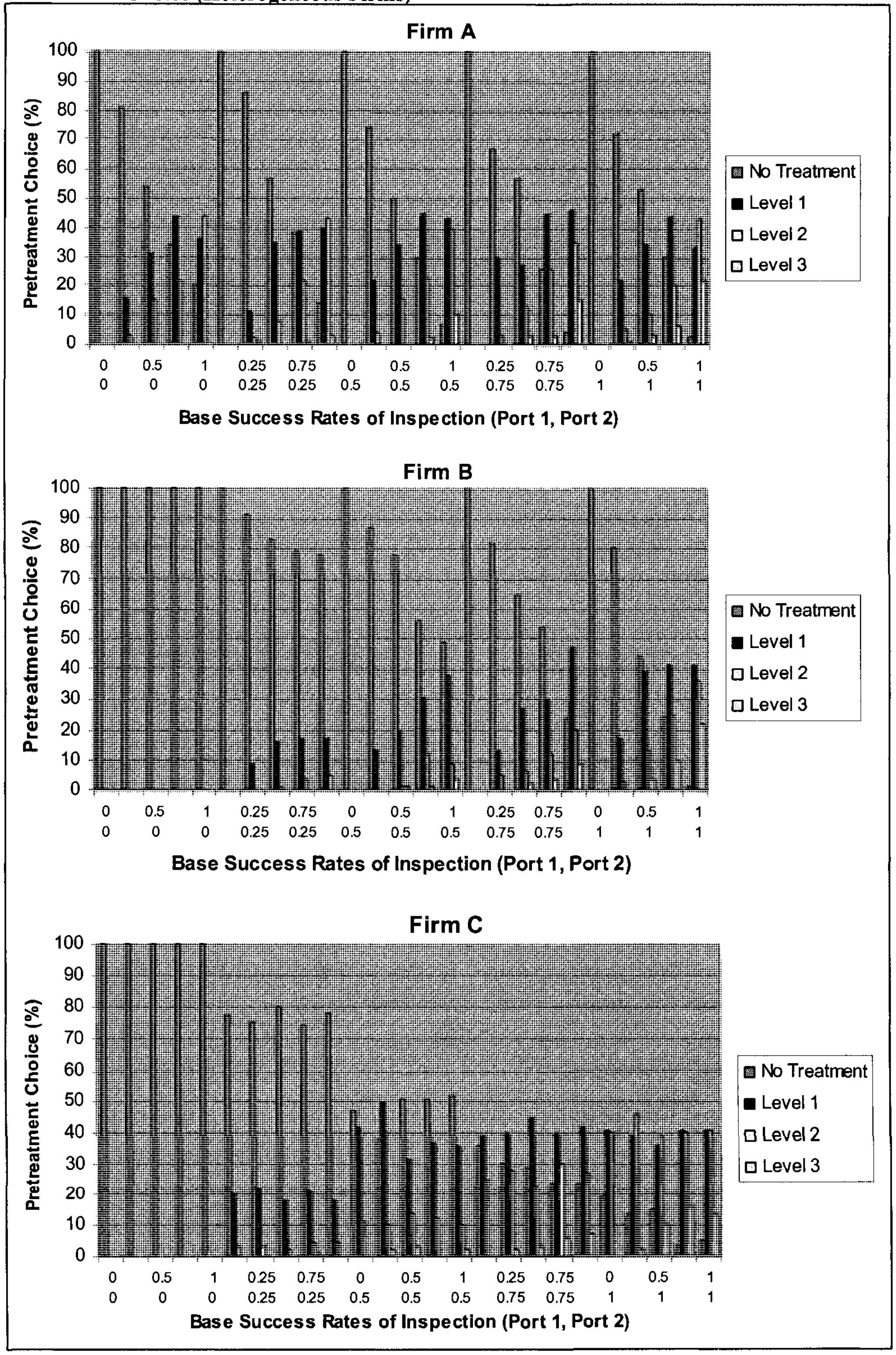
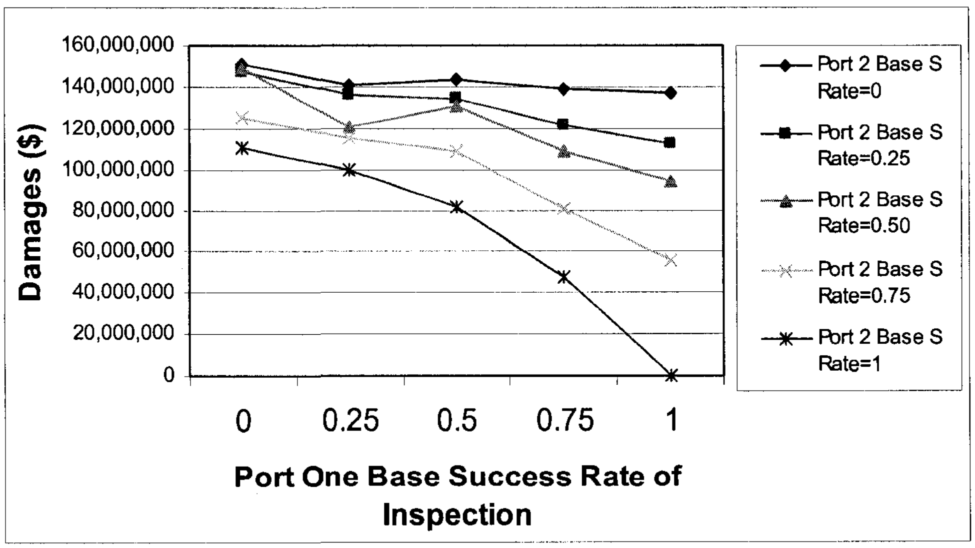


Figure 6-7: Base Success Rates of Inspection by Port and the Frequency of Pretreatment Choice (Heterogeneous Firms)



The effects of the base success rates of inspections on damages to broccoli crops follow similar paths to those of the base rates of inspection for both the homogeneous and heterogeneous firms although. While the path is similar, overall the damages are lower than when examining the effects of the base inspection rates. This may be due to the fact than in this scenario, each shipment is being inspected at a different success rate of inspection whereas in the prior scenario, the percentage of shipments inspected was variable. These results are shown in Figure 6-8. When the base rate of inspection or the success rate of inspection at port two is higher, the damages to the broccoli crops are lower due to the preference of firm A (with a 100 percent infection rate) to ship to port two. The more incentive a higher risk firm has to engage in pretreatment efforts, the less potential there will be for crop damages.

Figure 6-8: Base Success Rates of Inspection by Port and Broccoli Crop Damage (Heterogeneous Firms)



The differences between the damages when varying the base inspection rates and the base success rates raised the idea of a potential tradeoff effect between the two rates at the same port. If a port had lower (higher) base inspection rates and higher (lower) base success rates of inspection, would this lead to more or less damage to broccoli crops? Is it possible to substitute one inspection rate for another? This scenario was explored using heterogeneous firms and not homogeneous firms due to the greater variability of firms' responses when they are heterogeneous. In each scenario, the other port was held constant with a base rate of inspection (ρ_j) of 100 percent and a base success rate of inspection (β_j) of 1.0. The results of changing the inspection rates at port one are presented in Figure 6-9 below while the results from port two are shown in Figure 6-10.

Figure 6-9: Port One Base Inspection Rates with Base Success Rates of Inspection and Broccoli Crop Damage (Heterogeneous Firms)

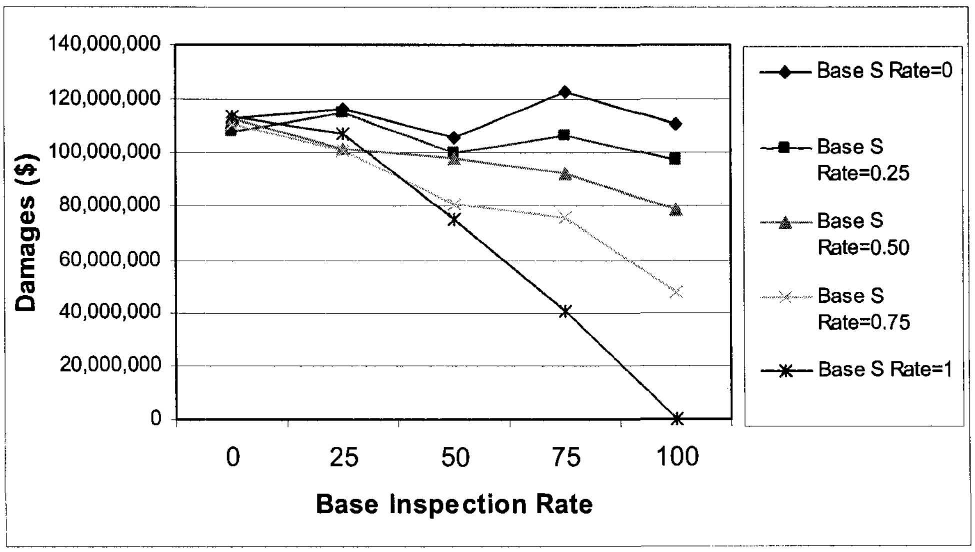
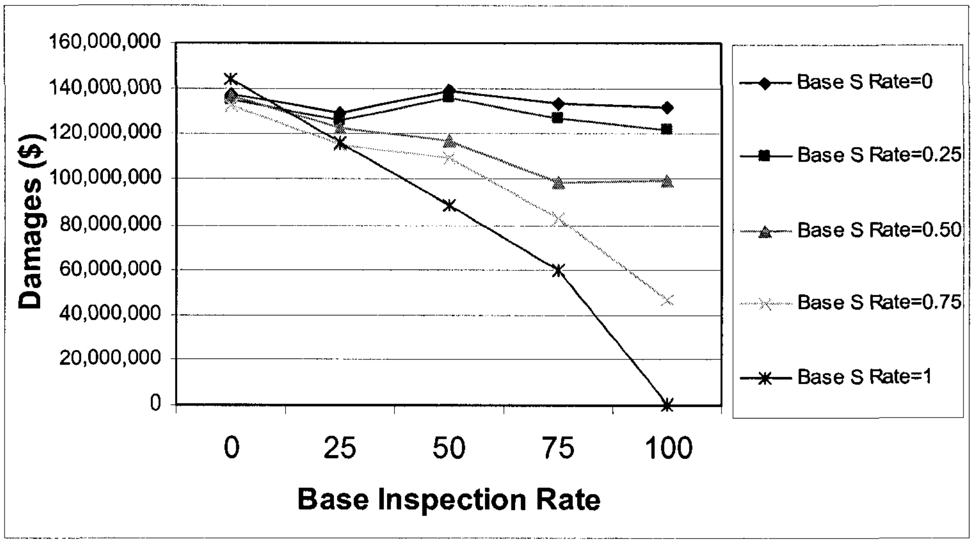


Figure 6-10: Port Two Base Inspection Rates with Base Success Rates of Inspection and Broccoli Crop Damage (Heterogeneous Firms)



The greatest damage at both ports occurs when either the base inspection rates or the base success rates of inspection are equal to zero. The least amount of damage occurs when both rates are on the higher side. In the case of port two, the overall cost of the damage to the broccoli crops are higher and remain consistently high until both rates are sufficiently high ($\rho_2 > 50$ and $\beta_2 > 0.5$). The damages are greater when varying the rates at port two than those at port one again due to the fact that the firm with the greatest infection rate (firm A at 100 percent) prefers to send their shipments through port two. If an infected shipment from firm A gets through the port, there is a greater likelihood that the pest will establish and spread in an area with broccoli than that of either firm B (with a 55 percent infection rate) or firm C (with a 10 percent infection rate). It does not appear as though the rates can be used as substitutes but rather that the rates are complementary.

Base inspection rates and the base success rates of inspection have a large effect on the pretreatment efforts of the firms. As these rates increase, firms choose to pretreat more frequently and at higher levels provided that the rates among ports are similar. Having ports that are more homogenous may help to reduce invasive species risk. The results of running the model with heterogeneous firms helped to illustrate this point. Increasing the base inspection rate or the base success rate of inspections at one port may help target some of the importers but there is the potential for adverse effects by others. Some firms will choose to continue shipping at the port with higher rates by increasing their pretreatment efforts whereas others will choose to avoid that port. To gain the greatest benefit, inspectors should aim to have their ports inspect at the highest level possible with the highest success rate as possible and attempt to minimize the differences between the ports.

6.1.2 Importer Specific Inspections

With the parameters set in the model scenarios above, the firms' dominant strategy was to consistently engage in pretreatment efforts to avoid the costs of being caught with an infected shipment. In order to examine the effects of importer specific inspection rates, some of the model parameters had to be relaxed. It was necessary to remove the consequences of being discovered with an infected shipment in order to entice firms to send infected shipments to the border. Under these conditions, inspectors would then be able to demonstrate their ability to identify violating firms and respond accordingly by increasing the inspection rates on those firms.

Two model specifications were run to compare damages to broccoli crops; one where the inspectors have the ability to learn who is a violating firm (n_i) and react by increasing that firm's future inspection rate ($\theta = 100$) and one where they can identify a violation but do not update their knowledge for future inspections ($\theta = 0$). The base rate of inspection (ρ_j) was set to 25 percent in order to allow for the increased inspection rate as a result of a firm being caught violating and the base success rate of an inspection was set to 0.5.

Results of this model specification demonstrate that, when inspectors have the ability to identify and respond to violating firms by increasing their importer specific inspection rates, broccoli crop damage can be reduced. When inspectors were not able to learn to respond to a violating firm, damage to broccoli crops was calculated to be $150,410,422.59. When the inspectors had the ability to update their inspection rates depending on the history of violations by a firm, damage to broccoli crops was calculated to be $131,891,770.93, a reduction in damage of approximately 12.3 percent. Without the consequences of being caught with an infected shipment, firms do not have any incentive to engage in pretreatment efforts, despite the fact that they may be faced with an increased rate of inspection for being caught with an infected shipment. When attempting to incorporate violation consequences for the importers, because of the assumption of perfect knowledge, firms will know if they are going to be inspected and will not risk being caught with an infected shipment thus not providing the inspectors with an opportunity to learn to identify offenders.

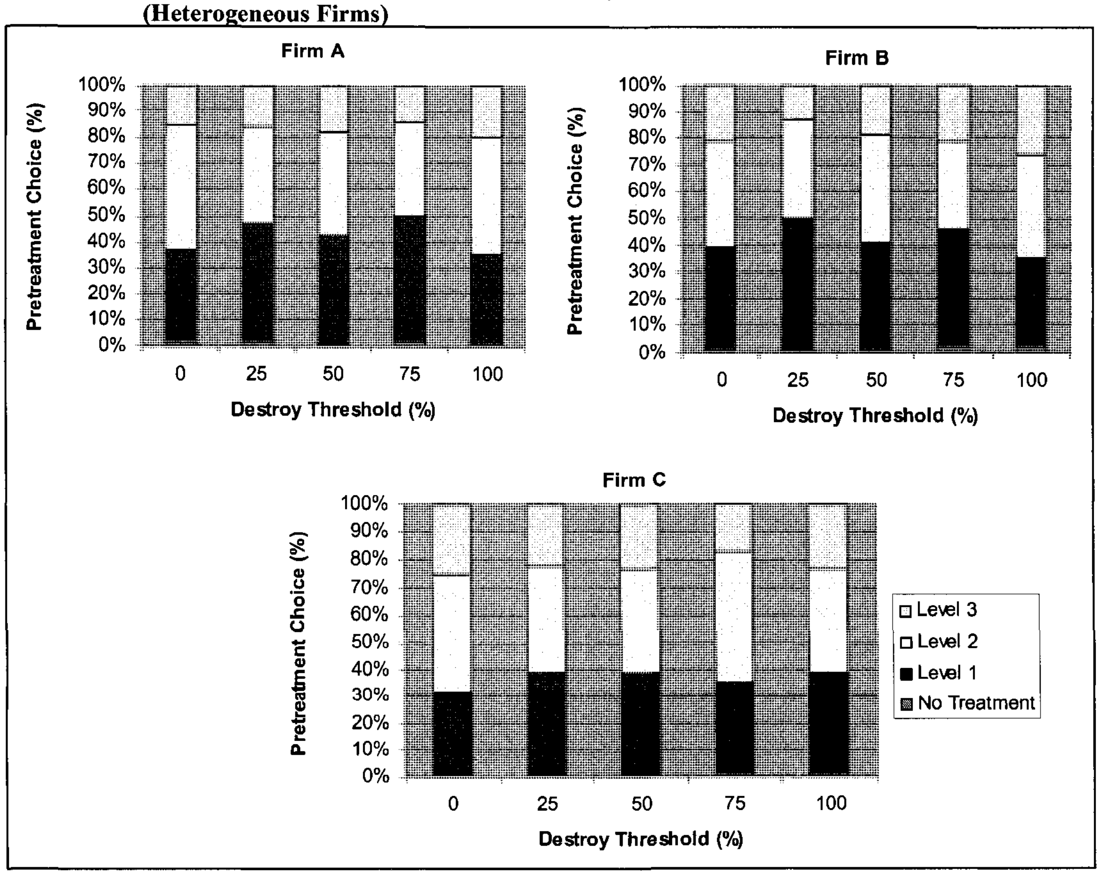
6.1.3 Inspector Decision: Treat or Destroy

In the agent-based model, inspectors have the ability to either destroy a discovered infected shipment or to treat it at the border. Unlike base inspection rates and base success rates of inspection, the decision to treat or destroy an infected shipment is set equal across ports. If the shipment is destroyed ($\gamma = 1$), the importer loses the value of their shipment (v_i) in addition to facing a fine (f). If the shipment is treated ($\gamma = 0$), the importer must pay for the treatment (r) as well as the fine (f). Whether or not the inspectors' choose to treat or destroy an infected shipment depends upon the level of damage that is already occurring in the broccoli crops (under the assumption of allowable loss). If the damage to the broccoli crops as a percentage of total crops is greater than the threshold percentage, the inspectors will choose to treat an infected shipment otherwise they will choose to destroy it. By changing the threshold value, it is possible to see the effect that the treat or destroy decision has on importers. According to the results found by Ameden, Cash and Zilberman (2007), an increase in the decision to destroy infected shipments results in an increase in pretreatment in order to avoid losing the shipment altogether.

When looking at the effects of the inspectors' choice between treating and destroying an infected shipment for the homogeneous importers in the agent-based model, the homogeneous importers did not appear to be influenced by changes in the treat vs. destroy threshold. This may have been explained by the violation fine being set too high. In examining the effects of changing the treat vs. destroy threshold in the heterogeneous importers, the violation fine was set to zero and the value of the treat/destroy threshold was increased from 0 to 100 percent in 25 percent increments. As the treat/destroy threshold is applied equally at each port and all other port rates are held the same between the ports, it is to be expected that each firm will choose send their shipments to the port with the lowest transportation cost.

The results of changing the treat vs. destroy threshold on importers' pretreatment choices are summarized in Figure 6-11 below. All of the firms sent their shipments to the port where their respective transportation costs were the lowest.

Figure 6-11: Treat/Destroy Threshold and the Frequency of Pretreatment Choice (Heterogeneous Firms)



Despite setting the violation fine to zero, like the case of the homogeneous firms, there still does not seem to be an effect of changing the treat vs. destroy threshold on the behavior of the heterogeneous importers. Each firms' pretreatment choice frequency does not seem to be influenced by a change in the threshold. Contrary to the results found by Ameden, Cash and Zilberman (2007), the agent-based model results suggest that importers do not behave differently when they could potentially lose their shipment from when they would have to pay for treatment of an infected shipment at the border; heterogeneous importers would rather pay for treatment at the point of origin.

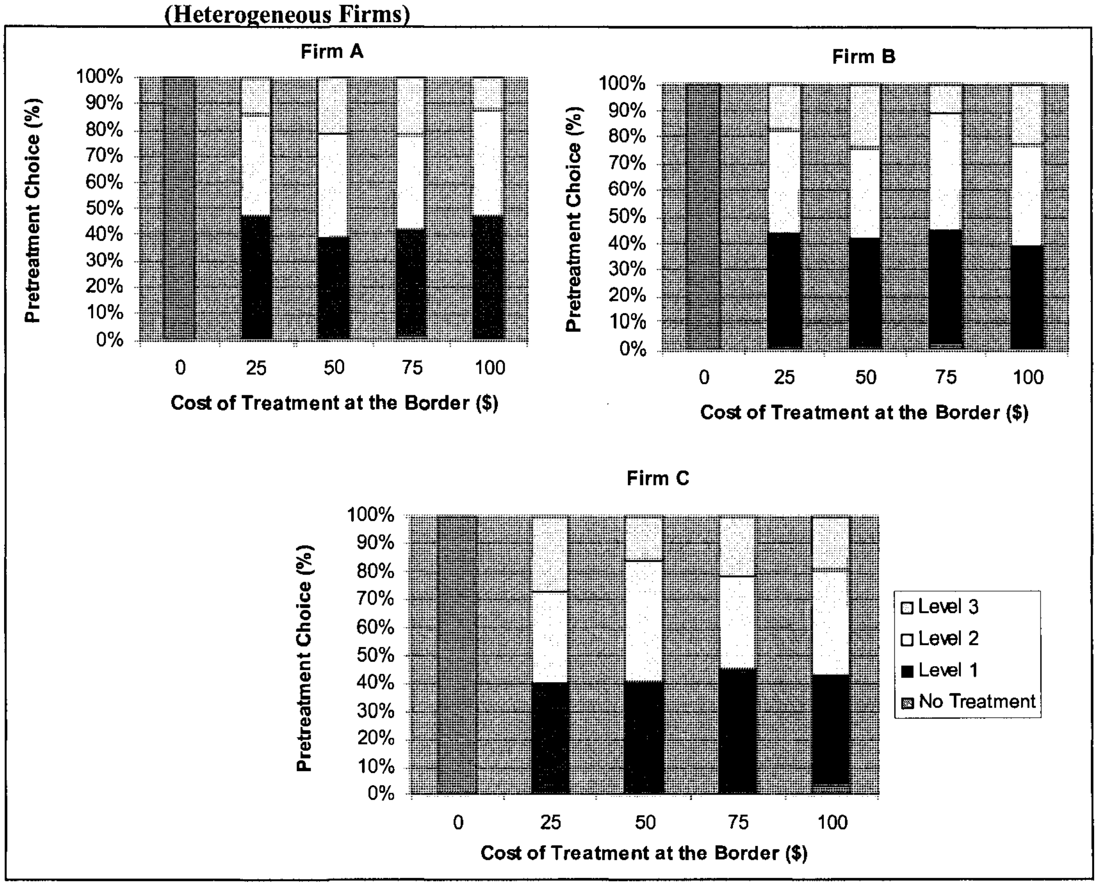
6.1.4 Violation Fine and Border Treatment Costs

Prior research on fines and enforcement has indicated that fines should be set arbitrarily high to deter firms from violating (Becker 1968). According to Malik (1990), this will lead to increased avoidance behavior by the firms and instead the optimal fines should be set lower than previous research suggested. The impact of violation fines in the agent-based model were explored by increasing the fine for being caught with an infected treatment from no fine up to $1000 in increments of $100 to determine what effect this would have on firms' pretreatment decision. The fine for an importer being caught with an infected shipment does not vary by port; the violation fines are consistent across ports. In this model specification, the base rate of inspection was set to 50 percent at both ports to see if a higher fine was more of a deterrent to lower pretreatment efforts than a lower inspection rate might be to encourage it. The results of running this specification of the model showed that every positive value of the fine resulted in a similar high pretreatment response by the importers. This raised concerns over whether or not the initial jump from no fine to $100 was too high. The model was then run using smaller increments for the fine in order to determine if the magnitude of the violation fine was too large or if any positive level of fine leads to the same result.

According to these model runs, including those using a finer fine scale, an increase in the violation fine does not translate into an increase in pretreatment efforts by the firms. This may be due to the fact that inspection levels are low enough that firms do not anticipate being discovered with an infected treatment or that firms are dissuaded not by the fine but rather the consequences of border treatment costs or losing their shipment altogether. When the border treatment costs were set to zero and inspectors chose to treat rather than destroy infected shipments, firms choose to use pretreatment efforts so long as the fine was greater than their costs of pretreatment. If the only consequence of being caught with an infected treatment was the fine and the fine was lower than their pretreatment costs, firms did not pretreat. These results provide support for Malik's (1990) suggestion that fines need not be set arbitrarily high in order to be effective, in this case, fines only have to be higher than the cost of the behavior that is desirable; for this model, that is the pretreatment effort.

In addition to examining the effects of the violation fine, the cost of treatment at the border for a discovered infected shipment was also examined. Would the benefit of lower treatment costs at the border outweigh the costs of being caught with an infected treatment? The effects of increasing the border treatment cost from zero to $100 per unit of shipment (in increments of $25) on the heterogeneous importers' pretreatment efforts were examined and are presented in Figure 6-12. Based upon the results found when running this model specification with the homogeneous firms, in this scenario with heterogeneous firms, the violation fine was reduced to zero.

Figure 6-12: Cost of Pretreatment at the Border and the Frequency of Pretreatment Choice (Heterogeneous Firms)



Firms once again chose to send their shipments to the port which had their lowest transportation cost. When the border treatment cost was set to zero, firms took advantage of this opportunity by choosing not to pretreat at the point of origin which resulted in violations for the firms but not a violation fine. Once the cost of treatment at the border was equal to or greater than pretreatment costs, importers pretreatment efforts were no longer affected by border treatment costs.

6.2 Other Influences on Importer Behavior

While the decisions made by the inspectors have a large influence on the actions of the importers, they are not the only factor that importers take into account when choosing their behavior. Costs faced by importers also play a major role in determining importer actions and could potentially outweigh or undermine the actions taken by the inspectors. By identifying these other influences, border enforcement policies could potentially be extended into areas beyond ports and inspections.

6.2.1 Pretreatment Costs and Effectiveness

Presumably, as pretreatment costs increase, importers should choose to use less of that pretreatment level. But if the cost being caught with an infected treatment is high enough, it may be worth the importers' while to maintain or increase their use of their chosen pretreatment level despite increasing costs. In order to examine the effects of the cost of pretreatment on heterogeneous importers' pretreatment choice, each level of pretreatment's cost was increased in increments of $25 from zero to $100. The results of increasing the cost of pretreatment level one on the firms' pretreatment choice are illustrated in Figure 6-13 while those of level two can be found in Figure 6-14. Finally, the results of increasing the cost of pretreatment level three is shown in Figure 6-15.

Figure 6-13: Cost of Pretreatment Level 1 and the Frequency of Pretreatment Choice (Heterogeneous Firms)

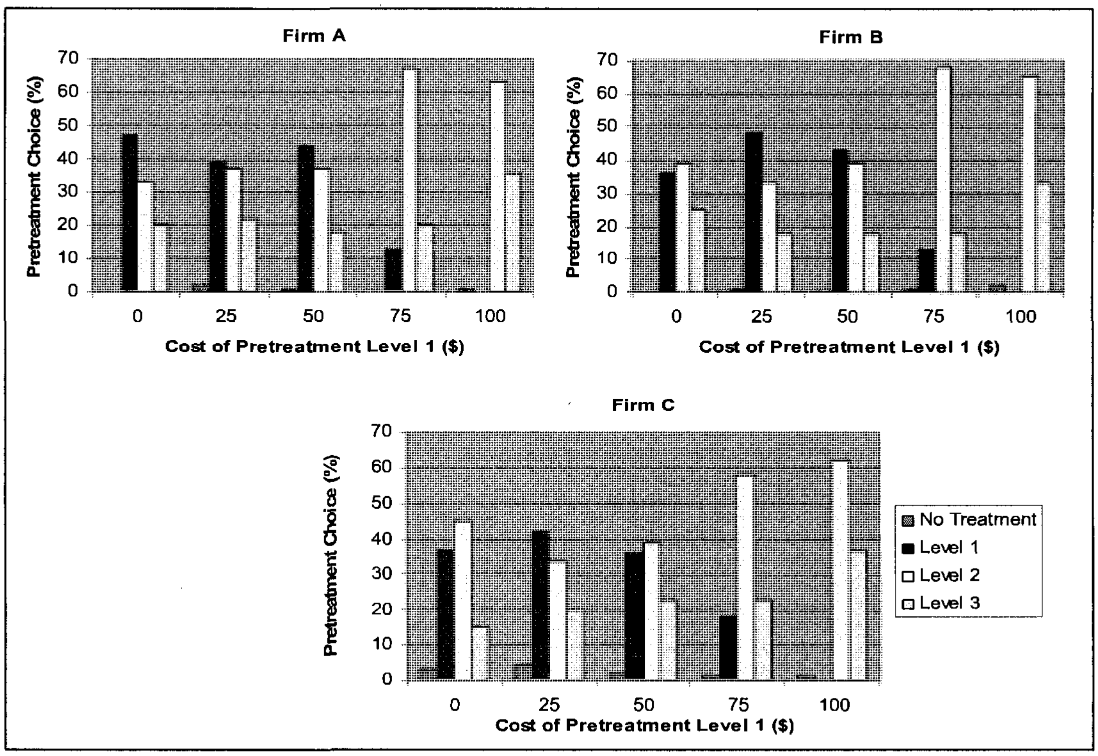


Figure 6-14: Cost of Pretreatment Level 2 and the Frequency of Pretreatment Choice (Heterogeneous Firms)

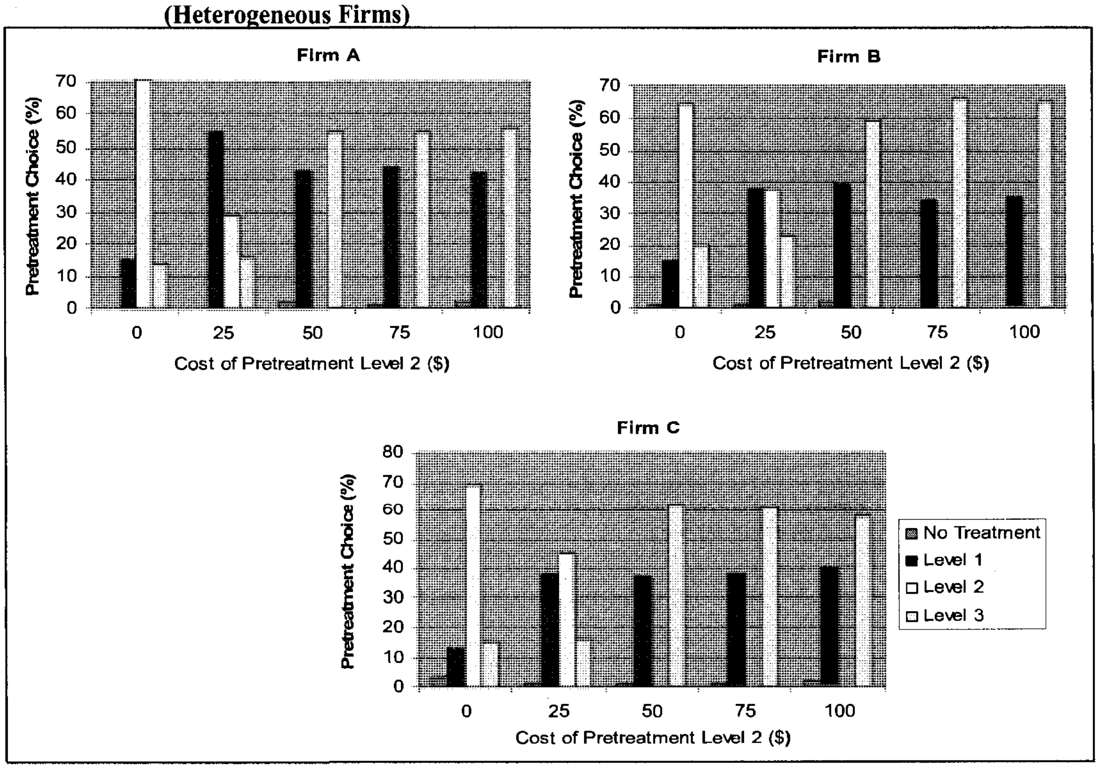
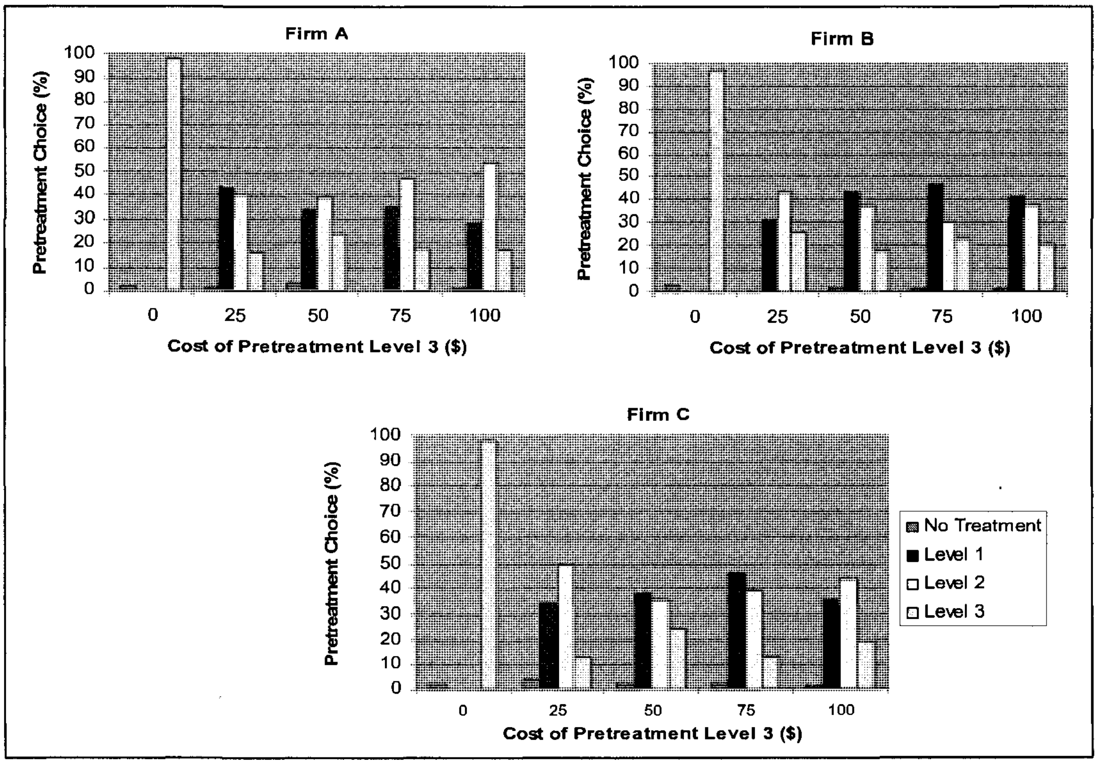


Figure 6-15: Cost of Pretreatment Level 3 and the Frequency of Pretreatment (Heterogeneous Firms)



The largest increase in use that occurs for all three firms is for the third level of pretreatment. This can be attributed to the fact that each level of pretreatment is scaled such that choosing a higher level of pretreatment will yield a greater probability that the pretreatment efforts were successful even if a lower level of pretreatment is performing to its highest ability. With a scalar factor of 1.0, pretreatment level three will be guaranteed in this model to eliminate the infection (recall that pretreatment effectiveness for level three is set at 100 percent) and may therefore be worth purchasing at higher price points. As the costs of other pretreatment levels increase and pretreatment level three becomes relatively more affordable, the importers begin to substitute towards level three. As the cost of pretreatment level three increases, there is still a slight increase in its demand after the initial drop-off from free to $25. Because the effects of pretreatment costs are internal to the firm (whereas transportation costs are external), it was to be expected that the different types of firms would respond similarly to a change in the pretreatment price.

In addition to examining the effects of the cost of pretreatment, the model was also run examining the effects of pretreatment effectiveness. Again, firms responded predictably. As the effectiveness level of one pretreatment level increased (while the others remained constant), importers began to select that level of pretreatment more often.

Importers respond predictably to increases in pretreatment costs and pretreatment effectiveness. Regulators may have more success in reducing invasive species risk by targeting the pretreatment costs and effectiveness rather than expending more effort at the ports. By making higher levels of pretreatment less costly and/or finding ways to increase the effectiveness of pretreatment levels, firms will have greater incentive to engage in pretreatment which makes them less likely to attempt to ship infected treatments.

6.3 Summary

The results of the agent-based model provided both expected and unexpected results. By increasing the base rate of inspections or the base success rates of inspection, firms will choose to engage in and increase their pretreatment efforts provided that the rates are consistent across the ports. Firms will also choose to increase their pretreatment efforts as the costs of doing so are decreased and/or the effectiveness of the pretreatment increases. By increasing inspection rates and/or increasing pretreatment efforts, the invasive species risk is reduced. Crop damages are reduced when inspectors have the ability to identify importers as higher risk firms based on their past performances. These results were intuitive and support some of the results found in the theoretical model. Despite making changes to the specifications to attempt to get at the effects of an increased violation fine, decreasing cost of border treatment and the treat vs. destroy threshold, it was found that these inspector decisions do not seem to play a role in decreasing invasive species risk. These results were unexpected and were contrary to some of the results from the theoretical model. Results of the agent-based model indicated that importers' dominant strategy is to pretreat their shipments.

6.4 Implications

Results from the agent-based model suggest that invasive species risk may be reduced through both the direct actions of border enforcement agents as well as by other policy tools. By increasing both the base rate of inspections at the ports and the base success rates of inspection at each port, inspectors will be able to reduce the invasive species risk. As these rates increase, importing firms will increase their pretreatment efforts depending on their transportation costs to the port and, as a result, the potential damage costs to broccoli crops decrease. It is important for ports to have consistent rates with each other in order to reduce importers' opportunities to engage in port shopping and to help reduce the weakest-link component of the public good problem.

Another way to reduce invasive species risk suggested by the agent-based model is to lower costs of pretreatment efforts and/or increase pretreatment effectiveness. As the price decreases for a level of pretreatment, an importer is more likely to engage in its use. There is also potential for increased pretreatment use if the effectiveness of the pretreatment can be increased. By giving the importers more bang for their pretreatment buck, pretreatment efforts will increase, more pests will be destroyed at the point of origin which will decrease damages to the crops and could potentially decrease the need for higher inspection rates at the border.

In the specifications of this agent-based model, there were several parameters that provided to have no effect on importers' pretreatment efforts. Whether or not the inspectors chose to treat or destroy an infected shipment if one was discovered, did not impact the pretreatment efforts or the risk of damage to crops even when holding other potential influences to zero. The positive cost of treatment of an infected shipment at the border did not change importers' pretreatment behavior. Increasing violation fines did not result in increased pretreatment efforts on the importers' behalf, just the presence of a fine seemed to encourage pretreatment efforts. The results of the agent-based model, under the assumptions made, indicate that firms have a dominant strategy to engage in pretreatment efforts. Depending on the use of other parameter values and assumptions, these results may be subject to change.

Chapter 7: Summary and Conclusions

This final chapter provides a look at what policy implications are suggested by the results of the agent-based model as well as makes note of the limitations of this study. It offers conclusions and final thoughts about both invasive species risk as well as the suitability of the agent-based model for this exercise and finishes off with a look at how this work may be extended and adapted for future works.

7.1 Conclusions

This thesis has developed and created an agent-based model of border enforcement for the management of invasive species. In doing so, it has demonstrated the use of a new method of modelling trade related invasive species risk. It has incorporated both a theoretical model as well as a spatially explicit damage function in order to strengthen its foundation and give meaning to the results. The agent-based model developed helps to extend the theoretical model proposed by Ameden, Cash and Zilberman. The agent-based model incorporated the heterogeneity in the importers and the ports as well as provided a learning mechanism by which inspectors were able to identify repeat violating firms. By incorporating the spatially explicit damage function created by Brody, the results of the modelling exercises were able to demonstrate the ability of the crucifer flea beetles to spread and establish as well as provide estimates of potential real world damages. The agent-based model extended the work by Brody by adding human behaviors as a vector for invasive species introduction.

The use of agent-based modelling for the management of invasive species risk has been informative. Due to the low probability/high consequence nature of invasive species, agent-based models provide a safe place in which to test policies. They allow for the replication of real world phenomenon and can help gather data about invasive species risk that would otherwise be unavailable until an event had already occurred. The agent-based model allows the results of mitigation to be directly observed thus solving the uncertainty of the effectiveness of mitigation efforts.

Results of the agent-based model provided both expected and surprising results. Expected results included a reduction in broccoli crop damage as base inspection rates and/or the base success rate of inspections increased. This came about in a somewhat surprising way. Rather than having the damage to broccoli crops reduced by the inspectors discovering infected shipments, the damages were actually lowered through the increased pretreatment efforts of the importers as the response to the inspectors' behavior. The dominant strategy of importers was to engage in pretreatment efforts. The model also demonstrated that pretreatment efforts undertaken by importers can be influenced by both the cost of the pretreatment as well as the effectiveness of the pretreatment. In this model, importers did not seem to be influenced by the inspectors' decision whether to treat or destroy an infected shipment or by an increase in the violation fine.

The model provides scenarios in which the damages to broccoli crops are higher or lower depending on the actions of both the inspectors and importers. It provides information about how the importers will react to actions taken by the inspectors as well as other factors which influence importer decisions. This information may then be used to help policymakers answer questions concerning border enforcement and invasive species risk.

7.2 Policy Implications

Results from the agent-based modelling exercise can be used to help inform decisions regarding the mitigation of invasive species risk. Policymakers should focus their efforts on increasing the inspection rates at ports, increasing the ability of inspectors to be able to detect an infected shipment as well as promoting homogeneity between ports in these areas. Base rates of inspection and the ability to conduct a successful inspection are not substitutes for one another but are instead complements for each other. Being able to identify and penalize violating importers should help inspectors focus their inspections on higher risk firms although future work in this area would provide further information regarding importer response. While this model did not take into account the costs of inspections and as such cannot provide information on balancing the costs and the benefits of inspection, the damages that arose from undetected infected treatment were a large proportion of the value of the broccoli crops suggesting that investing in increasing inspection and inspection abilities may be well worth it. Policymakers should also be interested in investing in pretreatment technologies to help increase their effectiveness as well as consider ways in which to decrease their costs to the importing firms as this will as contribute to increased point-of-origin treatment.

7.3 Limitations

While this agent-based model has allowed for the exploration of invasive species risk, it has been case specific. The results found are unique to the examination of the impacts of the crucifer flea beetle on the Californian broccoli crops and as such, caution should be exercised when looking to apply the recommendations arising from this model to other invasive species and geographical locations. The results are dependent upon the parameters used and by setting different parameters and combinations of parameters, the results may vary. The ability to run additional specifications of the model was hampered by the length of time models took to run. Fortunately, the framework could be easily adapted to provide information on other crops and/or other invasive species.

In addition to the issue of specificity, this modelling exercise may have been limited by programming abilities and may benefit from examination by, or be extended by, a more experienced programmer.

7.4 Future Research

This model has the potential to be extended by future work in several ways. One of these would be to examine the effects of model parameters that were not explored in this thesis. The model could be run and rerun with a variety of combinations using different parameter values in order to examine parameter sensitivity. Further work may look into potential tradeoffs between different policy options such as providing importing firms with lower pretreatment costs/increased pretreatment effectiveness and inspection rates. The assumption of perfect information by the importers could be relaxed in order to determine what importers may do when they do not know the actions that inspectors are going to take and can only base their information on what has happened to them in previous periods. There is also the potential for work to be done on the effects of climate change in this model. Temperature effects drive the beetles' ability to establish and spread which has the ability to affect the overall damage to crops and the inspectors' decision to treat or destroy infected shipments.

In this model, the main strategy was on the part of the importing firms. They were looking to minimize their costs. There are other strategies that would be worth examining as well. One of these strategies that would be worth examining is to minimize inspector costs given a minimum acceptable loss of crop or to minimize crop loss subject to a given inspection budget. Inspection budgets could be endogenized by potentially constructing them as a function of the damages that accrued in the previous period. Another strategy would be to maximize the firm's profit which would be affected by the price of broccoli and the shipment quantity. In the theoretical model by Ameden, Cash and Zilberman, the importers were able to react to inspector behavior by changing the amount of output they shipped. In the agent-based model, the quantity shipped by the importers was determined exogenously. Historical prices and production responses could be examined to help endogenize price.

Finally, this model could also be adapted to examine the effects of other invasive species on different crops in other geographical locations to determine whether or not the risks of other invasive species find similar results.

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Appendix A: NetLogo programming code

```
;///////////////////////////////////////////////////////////////////////////////////////////////////////////
; BREED DECLARATIONS
;///////////////////////////////////////////////////////////////////////////////////////////////////////////
breed [ pests pest ]
breed [ pests_a1 pest_a1 ]
breed [ pests_a2 pest_a2 ]
breed [ pests_b pest_b ]
breed [ pests_c pest_c ]
breed [ pest-children pest-child  ]
;///////////////////////////////////////////////////////////////////////////////////////////////////////////

;///////////////////////////////////////////////////////////////////////////////////////////////////////////
; INSTANT VARIABLES DECLARATIONS
;///////////////////////////////////////////////////////////////////////////////////////////////////////////
pests-own [ age found_food reproduce]
pest-children-own []
patches-own [ food region food_org crop_ready establishment_prob taken]
;///////////////////////////////////////////////////////////////////////////////////////////////////////////

;///////////////////////////////////////////////////////////////////////////////////////////////////////////
; GLOBAL VARIABLES DECLARATIONS
;///////////////////////////////////////////////////////////////////////////////////////////////////////////
globals [
        ; variable for stats
        cumulative
        current_crop_count    ;the current amount of broccoli on the map (time dependent)
        crop_count            ;total amount of broccoli on the map (independent of time)
        damage                ;how much damage has been done to the crops
        cost                  ;how much damage has been done in dollars (cost = damage * constant ,
                                      where constant = value of crops)


        ; variables for time
        week                  ; variable that holds the current week
        time                  ; variable that holds how many weeks have past since simulation started
                                      (does not reset with year)

        ; variables for map
        kms_to_patches_ratio    ; variables for mapsize
        kms^2_to_patches_ratio  ; variables for mapsize
        food_per_patch          ; variable that holds how much food is on every patch

        ; variables that hold crop densities of broccoli growing regions in the state
        sanjoaq
        southcoast
        centralcoast
        imperial

        ; variables that hold if a company is infected (0 if clean and 1 if infected) [bi]
        a_infected
        b_infected
        c_infected
```

```
; variables that hold how much it cost for each company to ship to each port (for i firm to
        ship to j port)  [tij]
 a_port1_cost   ; port 1 (west) Otay Mesa
 a_port2_cost   ; port 2 (east) Calexico

 b_port1_cost   ; port 1 (west) Otay Mesa
 b_port2_cost   ; port 2 (east) Calexico

 c_port1_cost   ; port 1 (west) Otay Mesa
 c_port2_cost   ; port 2 (east) Calexico

; variables that hold how much each company ships
a_Q
b_Q
c_Q

; variables that hold how many times a company has been caught with infected shipments
        [ni]
port1_a_violations
port2_a_violations

port1_b_violations
port2_b_violations

port1_c_violations
port2_c_violations

;variable that holds the formula for additional violations (n/2)
port1_a_v
port2_a_v

port1_b_v
port2_b_v

port1_c_v
port2_c_v

; variable that holds pretreatment level [eil]
 pretreat_level0_a
 pretreat_level1_a
 pretreat_level2_a
 pretreat_level3_a

 pretreat_level0_b
 pretreat_level1_b
 pretreat_level2_b
 pretreat_level3_b

 pretreat_level0_c
 pretreat_level1_c
 pretreat_level2_c
 pretreat_level3_c

 ;variable for pretreatment success [pi]
 pretreat_s_a0
 pretreat_s_a1
```

```
  pretreat_s_a2
  pretreat_s_a3

  pretreat_s_b0
  pretreat_s_b1
  pretreat_s_b2
  pretreat_s_b3

  pretreat_s_c0
  pretreat_s_c1
  pretreat_s_c2
  pretreat_s_c3

 ;variable for pretreatment success
 a_pretreat_s
 b_pretreat_s
 c_pretreat_s

;variable that holds firm's choice of pretreatment level
 a_choice
 b_choice
 c_choice

 ;variable that holds firm's choice of pretreatment while calculating
 choice_a0
 choice_a1
 choice_a2
 choice_a3

 choice_b0
 choice_b1
 choice_b2
 choice_b3

 choice_c0
 choice_c1
 choice_c2
 choice_c3

;variable that holds pretreatment effectiveness level
pre_choice_a
pre_choice_b
pre_choice_c


;variable that holds firm's port decision
  a_port
  b_port
  c_port

; variable that holds how far a pest can move during an iteration
   pest_movement

   ; variable for inspections (at each port for each firm) [Ij]
   in_rate_port1_a
   in_rate_port2_a
```

```
in_rate_port1_b
in_rate_port2_b

in_rate_port1_c
in_rate_port2_c

;variables hold base success rate of inspection for a given level of  treatment
in_s_rate_port1_a0
in_s_rate_port2_a0
in_s_rate_port1_a1
in_s_rate_port2_a1
in_s_rate_port1_a2
in_s_rate_port2_a2
in_s_rate_port1_a3
in_s_rate_port2_a3

in_s_rate_port1_b0
in_s_rate_port2_b0
in_s_rate_port1_b1
in_s_rate_port2_b1
in_s_rate_port1_b2
in_s_rate_port2_b2
in_s_rate_port1_b3
in_s_rate_port2_b3

in_s_rate_port1_c0
in_s_rate_port2_c0
in_s_rate_port1_c1
in_s_rate_port2_c1
in_s_rate_port1_c2
in_s_rate_port2_c2
in_s_rate_port1_c3
in_s_rate_port2_c3

; variables for success rate of inspections (at each port for each firm) [Sj]
s_rate_port1_a0
s_rate_port1_a1
s_rate_port1_a2
s_rate_port1_a3
s_rate_port2_a0
s_rate_port2_a1
s_rate_port2_a2
s_rate_port2_a3

s_rate_port1_b0
s_rate_port1_b1
s_rate_port1_b2
s_rate_port1_b3
s_rate_port2_b0
s_rate_port2_b1
s_rate_port2_b2
s_rate_port2_b3

s_rate_port1_c0
s_rate_port1_c1
```

```
       s_rate_port1_c2
       s_rate_port1_c3
       s_rate_port2_c0
       s_rate_port2_c1
       s_rate_port2_c2
       s_rate_port2_c3

      ;variable for success of inspection
      a_s_rate_port1
      a_s_rate_port2

      b_s_rate_port1
      b_s_rate_port2

      c_s_rate_port1
      c_s_rate_port2

       ; variable for inspector choice (destroy=1 or treat=0) [?]
       inspector_choice

       ; variable for cost [ci]
       a_cost
       b_cost
       c_cost



     ]
;//////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////


;//////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
;IMPORTER AND INSPECTOR VARIABLE INITIALIZATION
;//////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
to var-setup

 ; IMPORTER PROPERTIES
 ; cost of shipping to each port for each company
 set a_port1_cost trans_cost_a_1
 set a_port2_cost trans_cost_a_2

 set b_port1_cost trans_cost_b_1
 set b_port2_cost trans_cost_b_2

 set c_port1_cost trans_cost_c_1
 set c_port2_cost trans_cost_c_2

 ; quantity of broccoli being ship by each company
 set a_Q  shipment_Q_a
 set b_Q  shipment_Q_b
 set c_Q  shipment_Q_c

 ; sets initial violations to zero for each company
set port1_a_violations 0
set port2_a_violations 0
```

```
set port1_b_violations 0
set port2_b_violations 0

set port1_c_violations 0
set port2_c_violations 0

;sets pretreatment effort
set pretreat_level1_a 1
set pretreat_level2_a 2
set pretreat_level3_a 3

set pretreat_level1_b 1
set pretreat_level2_b 2
set pretreat_level3_b 3

set pretreat_level1_c 1
set pretreat_level2_c 2
set pretreat_level3_c 3

 ;INSPECTOR PROPERITES
 ; set choice of inspector (destroy=1 or treat=0)
 set inspector_choice 1



end
;////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////


;////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
; SETUP DECLARATION
;////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
to setup

 ; Map initialize
 ; this section clears the map, imports an image for the map and sets cost (cost of damage done so
far) to zero
 clear-all
 import-pcolors filename
 set cost 0
 set damage 0

 ; Map properties
 ; this section sets up various properties of the map and also gives individual patches properties
 ; contains info regarding patch properties
 set kms_to_patches_ratio 1.47
 set kms^2_to_patches_ratio (kms_to_patches_ratio * kms_to_patches_ratio)
 set food_per_patch 22400000
 ; density of crops for various regions (% of area as broc)
 ; these values are derived from "http://pestdata.ncsu.edu/cropprofiles/docs/cabroccoli.html"
 set sanjoaq 0.006
 set southcoast 0.100
 set centralcoast 0.212
 set imperial 0.031
```

```
; set patches with region info
map_setup

; Map statistics
; makes use of temp to calculate how much broccoli is on the map when model is initialized
; sets crop_count and current_crop_count to how much broccoli is on the map
let temp 0
ask patches [set temp (temp + food)]
set crop_count ((temp / food_per_patch)* kms^2_to_patches_ratio)
set current_crop_count crop_count

;Time setup
set week 0    ; initializes week to zero
set time 0    ; initializes time to zero

;Initalize importer and inspector variables
var-setup

end

;//////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
; CLEAR DECLARATION
;//////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
; subroutine used to when one wants to stop the simulation and reset
to clear
  clear-all
end

;//////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
; GO DECLARATION
;//////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
; The main routine of the model, this contains how/what happens during each time step in the
simulation.
; First it checks the time of year to see if broccoli is growing in any region of the map, if it is then
; it sets a flag telling the model that broccoli in that region can be consumed by pests otherwise it
sets
; the flag telling the model that broccoli can not be consumed.
; Next it calculates how much broccoli remains on the map (this is done every 5 iterations since
this operation
; very demanding).
;

to go

  ;/////////////////////////////
  ; INSPECTOR CHOICE
  ;/////////////////////////////

  if (damage < destroy_threshold) [set inspector_choice 0]

  ;/////////////////////////////
  ; Crop availability
  ;/////////////////////////////
  ; reset effects of pest damage on map on yearly basis
  if week > 52 [ reset_map]
```

```
 ; effect of imperial valley harvest (regions 5 and 6)
 if week > 11 [ ask patches [if (region = 5 or region = 6) [set crop_ready 0] ]]
 if week > 34 [ ask patches [if (region = 5 or region = 6) [set crop_ready 1] ]]
 ; effect of san jaq  harvest (regions 7 and 8)
 if week > 27 [ ask patches [if (region = 7 or region = 8) and (pycor + 1 * pxcor > -40 ) [set
crop_ready 1]]]
 ;////////////////////////////

 ;////////////////////////////
 ; Current Crop Count
 ;////////////////////////////
 ; update crop count every 8 weeks
 if week mod 4 = 0 [
  let temp 0
  ask patches [set temp (temp + food)]
  set current_crop_count ((temp / food_per_patch) * kms^2_to_patches_ratio)
 ]
 ;////////////////////////////

;////////////////////////////
 ;  TRUCK INFECTION [bi]
 ;////////////////////////////
 if (random 100 < a_infection_rate) [set a_infected 1]
 if (random 100 < b_infection_rate) [set b_infected 1]
 if (random 100 < c_infection_rate) [set c_infected 1]
 ;////////////////////////////

 ;////////////////////////////
 ;CALCULATIONS
 ;////////////////////////////
; **FIRM A **
 let cost_a 0    ;;holds cost choice while going through the calculations
 let choice_a 0  ;;holds pretreatment choice while going through the calculations
 let s_rate_port1_a 0
 let s_rate_port2_a 0
 let pretreat_s_a 0
 set a_port 0

; **FOR FIRM A WITH NO PRETREATMENT TO PORT 1 AND 2**
set pre_choice_a 0
set choice_a0 0
set pretreat_s_a0 0
set s_rate_port1_a0  0
set s_rate_port2_a0  0

; pretreatment success
 if (random 100 > (pre_choice_a * choice_a0)) [set pretreat_s_a0 1]

;inspection calculation
set port1_a_v (port1_a_violations / 2)
set port2_a_v (port2_a_violations / 2)

set in_rate_port1_a (base_rate_of_in_port1 + (additional_violation_port1 * port1_a_v))
   if (in_rate_port1_a > 100) [set in_rate_port1_a 100]
set in_rate_port2_a (base_rate_of_in_port2 + (additional_violation_port2 * port2_a_v))
    if (in_rate_port2_a > 100) [set in_rate_port2_a 100]
```

```
;success of inspection
 set in_s_rate_port1_a0 (in_base_s_rate_port1 * in_rate_port1_a * a_infected * pretreat_s_a0)
    if (in_s_rate_port1_a0 > random 100) [set s_rate_port1_a0 1]
 set in_s_rate_port2_a0 (in_base_s_rate_port2 * in_rate_port2_a * a_infected * pretreat_s_a0)
    if (in_s_rate_port2_a0 > random 100) [set s_rate_port2_a0 1]


;cost calculation
  let cost_a_0_1 (a_port1_cost + (s_rate_port1_a0 * (inspector_choice * value_a * a_Q +
border_treatment_cost * (1 - inspector_choice) * a_Q + fine)))
  let cost_a_0_2 (a_port2_cost + (s_rate_port2_a0 * (inspector_choice * value_a * a_Q +
border_treatment_cost * (1 - inspector_choice) * a_Q + fine)))
 set cost_a cost_a_0_1 set a_port 1 set choice_a 0 set s_rate_port1_a  s_rate_port1_a0 set
pretreat_s_a pretreat_s_a0
 if (cost_a > cost_a_0_2) [set cost_a cost_a_0_2 set choice_a 0 set a_port 2 set s_rate_port2_a
s_rate_port2_a0 set pretreat_s_a pretreat_s_a0 ]

;**FOR FIRM A WITH LEVEL 1 PRETREATMENT TO PORT 1 AND 2**
  set pre_choice_a pretreatment_effectiveness1
  set choice_a1 0.4
  set pretreat_s_a1 0
  set s_rate_port1_a1  0
  set s_rate_port2_a1  0

 ;pretreatment success
 if (random 100 > (pre_choice_a * choice_a1)) [set pretreat_s_a1 1]

;inspection calculation
set port1_a_v (port1_a_violations / 2)
set port2_a_v (port2_a_violations / 2)

set in_rate_port1_a (base_rate_of_in_port1 + (additional_violation_port1 * port1_a_v))
   if (in_rate_port1_a > 100) [set in_rate_port1_a 100]
set in_rate_port2_a (base_rate_of_in_port2 + (additional_violation_port2 * port2_a_v))
    if (in_rate_port2_a > 100) [set in_rate_port2_a 100]

;success of inspection
 set in_s_rate_port1_a1 (in_base_s_rate_port1 * in_rate_port1_a * a_infected * pretreat_s_a1)
    if (in_s_rate_port1_a1 > random 100) [set s_rate_port1_a1 1]
 set in_s_rate_port2_a1 (in_base_s_rate_port2 * in_rate_port2_a * a_infected * pretreat_s_a1)
    if (in_s_rate_port2_a1 > random 100) [set s_rate_port2_a1 1]

;cost calculation
let cost_a_1_1 ((pretreat_level1_a * pre_cost1) + a_port1_cost + (s_rate_port1_a1 *
(inspector_choice * value_a * a_Q + border_treatment_cost *
            (1 - inspector_choice) * a_Q + fine)))
let cost_a_1_2 ((pretreat_level1_a * pre_cost1) + a_port2_cost + (s_rate_port2_a1 *
(inspector_choice * value_a * a_Q + border_treatment_cost *
             (1 - inspector_choice) * a_Q + fine)))
 if (cost_a > cost_a_1_1) [set cost_a cost_a_1_1 set choice_a 1 set a_port 1 set s_rate_port1_a
s_rate_port1_a1 set pretreat_s_a pretreat_s_a1]
 if (cost_a > cost_a_1_2) [set cost_a cost_a_1_2 set choice_a 1 set a_port 2 set s_rate_port2_a
s_rate_port2_a1 set pretreat_s_a pretreat_s_a1]
```

```
;**FOR FIRM A WITH LEVEL 2 PRETREATMENT TO PORT 1 AND 2**
 set pre_choice_a pretreatment_effectiveness2
 set choice_a2 0.65
 set pretreat_s_a2 0
 set s_rate_port1_a2  0
 set s_rate_port2_a2  0

;pretreatment success
 if (random 100 > (pre_choice_a * choice_a2)) [set pretreat_s_a2 1]

;inspection calculation
set port1_a_v (port1_a_violations / 2)
set port2_a_v (port2_a_violations / 2)

set in_rate_port1_a (base_rate_of_in_port1 + (additional_violation_port1 * port1_a_v))
   if (in_rate_port1_a > 100) [set in_rate_port1_a 100]
set in_rate_port2_a (base_rate_of_in_port2 + (additional_violation_port2 * port2_a_v))
   if (in_rate_port2_a > 100) [set in_rate_port2_a 100]

;success of inspection
 set in_s_rate_port1_a2 (in_base_s_rate_port1 * in_rate_port1_a * a_infected * pretreat_s_a2)
   if (in_s_rate_port1_a2 > random 100) [set s_rate_port1_a2 1]
 set in_s_rate_port2_a2 (in_base_s_rate_port2 * in_rate_port2_a * a_infected * pretreat_s_a2)
   if (in_s_rate_port2_a2 > random 100) [set s_rate_port2_a2 1]

;cost calculation
let cost_a_2_1 ((pretreat_level2_a * pre_cost2) + a_port1_cost + (s_rate_port1_a2 *
(inspector_choice * value_a * a_Q + border_treatment_cost *
          (1 - inspector_choice) * a_Q + fine)))
let cost_a_2_2 ((pretreat_level2_a * pre_cost2) + a_port2_cost + (s_rate_port2_a2 *
(inspector_choice * value_a * a_Q + border_treatment_cost *
          (1 - inspector_choice) * a_Q + fine)))
 if (cost_a > cost_a_2_1) [set cost_a cost_a_2_1 set choice_a 2 set a_port 1 set s_rate_port1_a
s_rate_port1_a2 set pretreat_s_a pretreat_s_a2]
 if (cost_a > cost_a_2_2) [set cost_a cost_a_2_2 set choice_a 2 set a_port 2 set s_rate_port2_a
s_rate_port2_a2 set pretreat_s_a pretreat_s_a2]


;**FOR FIRM A WITH LEVEL 3 PRETREATMENT TO PORT 1 AND 2**
 set pre_choice_a pretreatment_effectiveness3
 set choice_a3 1
 set pretreat_s_a3 0
 set s_rate_port1_a3  0
 set s_rate_port2_a3  0

;pretreatment success
 if (random 100 > (pre_choice_a * choice_a3)) [set pretreat_s_a3 1]

;inspection calculation
set port1_a_v (port1_a_violations / 2)
set port2_a_v (port2_a_violations / 2)

set in_rate_port1_a (base_rate_of_in_port1 + (additional_violation_port1 * port1_a_v))
   if (in_rate_port1_a > 100) [set in_rate_port1_a 100]
set in_rate_port2_a (base_rate_of_in_port2 + (additional_violation_port2 * port2_a_v))
   if (in_rate_port2_a > 100) [set in_rate_port2_a 100]
```

```
;success of inspection
 set in_s_rate_port1_a3 (in_base_s_rate_port1 * in_rate_port1_a * a_infected * pretreat_s_a3)
    if (in_s_rate_port1_a3 > random 100) [set s_rate_port1_a3 1]
 set in_s_rate_port2_a3 (in_base_s_rate_port2 * in_rate_port2_a * a_infected * pretreat_s_a3)
    if (in_s_rate_port2_a3 > random 100) [set s_rate_port2_a3 1]

;cost calculation
let cost_a_3_1 ((pretreat_level3_a * pre_cost3) + a_port1_cost + (s_rate_port1_a3 *
(inspector_choice * value_a * a_Q + border_treatment_cost *
            (1 - inspector_choice) * a_Q + fine)))
let cost_a_3_2 ((pretreat_level3_a * pre_cost3) + a_port2_cost + (s_rate_port2_a3 *
(inspector_choice * value_a * a_Q + border_treatment_cost *
             (1 - inspector_choice) * a_Q + fine)))
 if (cost_a > cost_a_3_1) [set cost_a cost_a_3_1 set choice_a 3 set a_port 1 set s_rate_port1_a
s_rate_port1_a3 set pretreat_s_a pretreat_s_a3]
 if (cost_a > cost_a_3_2) [set cost_a cost_a_3_2 set choice_a 3 set a_port 2 set s_rate_port2_a
s_rate_port2_a3 set pretreat_s_a pretreat_s_a3]


set a_cost  cost_a
set a_choice choice_a
set a_s_rate_port1 s_rate_port1_a
set a_s_rate_port2 s_rate_port2_a
set a_pretreat_s pretreat_s_a

; violation count by port for firm a
if (s_rate_port1_a0 = 1) and (a_choice = 0) and (a_port = 1) [set port1_a_violations
(port1_a_violations + 1)]
if (s_rate_port1_a1 = 1) and (a_choice = 0.4) and (a_port = 1) [set port1_a_violations
(port1_a_violations + 1)]
if (s_rate_port1_a2 = 1) and (a_choice = 0.65) and (a_port = 1) [set port1_a_violations
(port1_a_violations + 1)]
if (s_rate_port1_a3 = 1) and (a_choice = 1) and (a_port = 1) [set port1_a_violations
(port1_a_violations + 1)]

if (s_rate_port2_a0 = 1) and (a_choice = 0) and (a_port = 2) [set port2_a_violations
(port2_a_violations + 1)]
if (s_rate_port2_a1 = 1) and (a_choice = 0.4) and (a_port = 2) [set port2_a_violations
(port2_a_violations + 1)]
if (s_rate_port2_a2 = 1) and (a_choice = 0.65) and (a_port = 2) [set port2_a_violations
(port2_a_violations + 1)]
if (s_rate_port2_a3 = 1) and (a_choice = 1) and (a_port = 2) [set port2_a_violations
(port2_a_violations + 1)]


;** FIRM B**
  let cost_b 0    ;;holds cost choice while going through the calculations
  let choice_b 0  ;;holds pretreatment choice while going through the calculations
  let s_rate_port1_b 0
  let s_rate_port2_b 0
  let pretreat_s_b 0
  set b_port 0

; **FOR FIRM B WITH NO PRETREATMENT TO PORT 1 AND 2**
set pre_choice_b 0
```

```
set choice_b0 0
set pretreat_s_b0 0
set s_rate_port1_b0  0
set s_rate_port2_b0  0

; pretreatment success
 if (random 100 > (pre_choice_b * choice_b0)) [set pretreat_s_b0 1]

;inspection calculation
set port1_b_v (port1_b_violations / 2)
set port2_b_v (port2_b_violations / 2)

;set in_rate_port1_b (base_rate_of_in_port1 + (additional_violation_port1 * port1_b_v))
   if (in_rate_port1_b > 100) [set in_rate_port1_b 100]
set in_rate_port2_b (base_rate_of_in_port2 + (additional_violation_port2 * port2_b_v))
    if (in_rate_port2_b > 100) [set in_rate_port2_b 100]

;success of inspection
 set in_s_rate_port1_b0 (in_base_s_rate_port1 * in_rate_port1_b * b_infected * pretreat_s_b0)
    if (in_s_rate_port1_b0 > random 100) [set s_rate_port1_b0 1]
 set in_s_rate_port2_b0 (in_base_s_rate_port2 * in_rate_port2_b * b_infected * pretreat_s_b0)
    if (in_s_rate_port2_b0 > random 100) [set s_rate_port2_b0 1]


;cost calculation
  let cost_b_0_1 (b_port1_cost + (s_rate_port1_b0 * (inspector_choice * value_b * b_Q +
border_treatment_cost * (1 - inspector_choice) * b_Q + fine)))
  let cost_b_0_2 (b_port2_cost + (s_rate_port2_b0 * (inspector_choice * value_b * b_Q +
border_treatment_cost * (1 - inspector_choice) * b_Q + fine)))
 set cost_b cost_b_0_1 set b_port 1 set choice_b 0 set s_rate_port1_b  s_rate_port1_b0 set
pretreat_s_b pretreat_s_b0
 if (cost_b > cost_b_0_2) [set cost_b cost_b_0_2 set choice_b 0 set b_port 2 set s_rate_port2_b
s_rate_port2_b0 set pretreat_s_b pretreat_s_b0 ]

;**FOR FIRM B WITH LEVEL 1 PRETREATMENT TO PORT 1 AND 2**
  set pre_choice_b pretreatment_effectiveness1
  set choice_b1 0.4
  set pretreat_s_b1 0
  set s_rate_port1_b1  0
  set s_rate_port2_b1  0

 ;pretreatment success
 if (random 100 > (pre_choice_b * choice_b1)) [set pretreat_s_b1 1]

;inspection calculation
set port1_b_v (port1_b_violations / 2)
set port2_b_v (port2_b_violations / 2)

set in_rate_port1_b (base_rate_of_in_port1 + (additional_violation_port1 * port1_b_v))
   if (in_rate_port1_b > 100) [set in_rate_port1_b 100]
set in_rate_port2_b (base_rate_of_in_port2 + (additional_violation_port2 * port2_b_v))
    if (in_rate_port2_b > 100) [set in_rate_port2_b 100]

;success of inspection
 set in_s_rate_port1_b1 (in_base_s_rate_port1 * in_rate_port1_b * b_infected * pretreat_s_b1)
    if (in_s_rate_port1_b1 > random 100) [set s_rate_port1_b1 1]
```

```
 set in_s_rate_port2_b1 (in_base_s_rate_port2 * in_rate_port2_b * b_infected * pretreat_s_b1)
   if (in_s_rate_port2_b1 > random 100) [set s_rate_port2_b1 1]

;cost calculation
let cost_b_1_1 ((pretreat_level1_b * pre_cost1) + b_port1_cost + (s_rate_port1_b1 *
(inspector_choice * value_b * b_Q + border_treatment_cost *
          (1 - inspector_choice) * b_Q + fine)))
let cost_b_1_2 ((pretreat_level1_b * pre_cost1) + b_port2_cost + (s_rate_port2_b1 *
(inspector_choice * value_b * b_Q + border_treatment_cost *
          (1 - inspector_choice) * b_Q + fine)))
 if (cost_b > cost_b_1_1) [set cost_b cost_b_1_1 set choice_b 1 set b_port 1 set s_rate_port1_b
s_rate_port1_b1 set pretreat_s_b pretreat_s_b1]
 if (cost_b > cost_b_1_2) [set cost_b cost_b_1_2 set choice_b 1 set b_port 2 set s_rate_port2_b
s_rate_port2_b1 set pretreat_s_b pretreat_s_b1]

;**FOR FIRM B WITH LEVEL 2 PRETREATMENT TO PORT 1 AND 2**
 set pre_choice_b pretreatment_effectiveness2
 set choice_b2 0.65
 set pretreat_s_b2 0
 set s_rate_port1_b2  0
 set s_rate_port2_b2  0

 ;pretreatment success
 if (random 100 > (pre_choice_b * choice_b2)) [set pretreat_s_b2 1]

;inspection calculation
set port1_b_v (port1_b_violations / 2)
set port2_b_v (port2_b_violations / 2)

set in_rate_port1_b (base_rate_of_in_port1 + (additional_violation_port1 * port1_b_v))
   if (in_rate_port1_b > 100) [set in_rate_port1_b 100]
set in_rate_port2_b (base_rate_of_in_port2 + (additional_violation_port2 * port2_b_v))
   if (in_rate_port2_b > 100) [set in_rate_port2_b 100]

;success of inspection
 set in_s_rate_port1_b2 (in_base_s_rate_port1 * in_rate_port1_b * b_infected * pretreat_s_b2)
   if (in_s_rate_port1_b2 > random 100) [set s_rate_port1_b2 1]
 set in_s_rate_port2_b2 (in_base_s_rate_port2 * in_rate_port2_b * b_infected * pretreat_s_b2)
   if (in_s_rate_port2_b2 > random 100) [set s_rate_port2_b2 1]

;cost calculation
let cost_b_2_1 ((pretreat_level2_b * pre_cost2) + b_port1_cost + (s_rate_port1_b2 *
(inspector_choice * value_b * b_Q + border_treatment_cost *
          (1 - inspector_choice) * b_Q + fine)))
let cost_b_2_2 ((pretreat_level2_b * pre_cost2) + b_port2_cost + (s_rate_port2_b2 *
(inspector_choice * value_b * b_Q + border_treatment_cost *
          (1 - inspector_choice) * b_Q + fine)))
 if (cost_b > cost_b_2_1) [set cost_b cost_b_2_1 set choice_b 2 set b_port 1 set s_rate_port1_b
s_rate_port1_b2 set pretreat_s_b pretreat_s_b2]
 if (cost_b > cost_b_2_2) [set cost_b cost_b_2_2 set choice_b 2 set b_port 2 set s_rate_port2_b
s_rate_port2_b2 set pretreat_s_b pretreat_s_b2]


;**FOR FIRM B WITH LEVEL 3 PRETREATMENT TO PORT 1 AND 2**
 set pre_choice_b pretreatment_effectiveness3
 set choice_b3 1
```

```
 set pretreat_s_b3 0
 set s_rate_port1_b3  0
 set s_rate_port2_b3  0

 ;pretreatment success
 if (random 100 > (pre_choice_b * choice_b3)) [set pretreat_s_b3 1]

;inspection calculation
set port1_b_v (port1_b_violations / 2)
set port2_b_v (port2_b_violations / 2)

set in_rate_port1_b (base_rate_of_in_port1 + (additional_violation_port1 * port1_b_v))
   if (in_rate_port1_b > 100) [set in_rate_port1_b 100]
set in_rate_port2_b (base_rate_of_in_port2 + (additional_violation_port2 * port2_b_v))
    if (in_rate_port2_b > 100) [set in_rate_port2_b 100]

;success of inspection
set in_s_rate_port1_b3 (in_base_s_rate_port1 * in_rate_port1_b * b_infected * pretreat_s_b3)
    if (in_s_rate_port1_b3 > random 100) [set s_rate_port1_b3 1]
 set in_s_rate_port2_b3 (in_base_s_rate_port2 * in_rate_port2_b * b_infected * pretreat_s_b3)
    if (in_s_rate_port2_b3 > random 100) [set s_rate_port2_b3 1]

;cost calculation
let cost_b_3_1 ((pretreat_level3_b * pre_cost3) + b_port1_cost + (s_rate_port1_b3 *
(inspector_choice * value_b * b_Q + border_treatment_cost *
              (1 - inspector_choice) * b_Q + fine)))
let cost_b_3_2 ((pretreat_level3_b * pre_cost3) + b_port2_cost + (s_rate_port2_b3 *
(inspector_choice * value_b * b_Q + border_treatment_cost *
               (1 - inspector_choice) * b_Q + fine)))
 if (cost_b > cost_b_3_1) [set cost_b cost_b_3_1 set choice_b 3 set b_port 1 set s_rate_port1_b
s_rate_port1_b3 set pretreat_s_b pretreat_s_b3]
 if (cost_b > cost_b_3_2) [set cost_b cost_b_3_2 set choice_b 3 set b_port 2 set s_rate_port2_b
s_rate_port2_b3 set pretreat_s_b pretreat_s_b3]

set b_cost  cost_b
set b_choice choice_b
set b_s_rate_port1 s_rate_port1_b
set b_s_rate_port2 s_rate_port2_b
set b_pretreat_s pretreat_s_b

; violation count by port for firm b
if (s_rate_port1_b0 = 1) and (b_choice = 0) and (b_port = 1) [set port1_b_violations
(port1_b_violations + 1)]
if (s_rate_port1_b1 = 1) and (b_choice = 0.4) and (b_port = 1) [set port1_b_violations
(port1_b_violations + 1)]
if (s_rate_port1_b2 = 1) and (b_choice = 0.65) and (b_port = 1) [set port1_b_violations
(port1_b_violations + 1)]
if (s_rate_port1_b3 = 1) and (b_choice = 1) and (b_port = 1) [set port1_b_violations
(port1_b_violations + 1)]

if (s_rate_port2_b0 = 1) and (b_choice = 0) and (b_port = 2) [set port2_b_violations
(port2_b_violations + 1)]
if (s_rate_port2_b1 = 1) and (b_choice = 0.4) and (b_port = 2) [set port2_b_violations
(port2_b_violations + 1)]
if (s_rate_port2_b2 = 1) and (b_choice = 0.65) and (b_port = 2) [set port2_b_violations
(port2_b_violations + 1)]
```

```
if (s_rate_port2_b3 = 1) and (b_choice = 1) and (b_port = 2) [set port2_b_violations
(port2_b_violations + 1)]


;**FIRM C**
 let cost_c 0    ;;holds cost choice while going through the calculations
 let choice_c 0  ;;holds pretreatment choice while going through the calculations
 let s_rate_port1_c 0
 let s_rate_port2_c 0
 let pretreat_s_c 0
 set c_port 0

 ; **FOR FIRM C WITH NO PRETREATMENT TO PORT 1 AND 2**
set pre_choice_c 0
set choice_c0 0
set pretreat_s_c0 0
set s_rate_port1_c0  0
set s_rate_port2_c0  0

; pretreatment success
 if (random 100 > (pre_choice_c * choice_c0)) [set pretreat_s_c0 1]

;inspection calculation
set port1_c_v (port1_c_violations / 2)
set port2_c_v (port2_c_violations / 2)

set in_rate_port1_c (base_rate_of_in_port1 + (additional_violation_port1 * port1_c_v))
   if (in_rate_port1_c > 100) [set in_rate_port1_c 100]
set in_rate_port2_c (base_rate_of_in_port2 + (additional_violation_port2 * port2_c_v))
    if (in_rate_port2_c > 100) [set in_rate_port2_c 100]

;success of inspection
 set in_s_rate_port1_c0 (in_base_s_rate_port1 * in_rate_port1_c * c_infected * pretreat_s_c0)
    if (in_s_rate_port1_c0 > random 100) [set s_rate_port1_c0 1]
 set in_s_rate_port2_c0 (in_base_s_rate_port2 * in_rate_port2_c * c_infected * pretreat_s_c0)
    if (in_s_rate_port2_c0 > random 100) [set s_rate_port2_c0 1]


;cost calculation
 let cost_c_0_1 (c_port1_cost + (s_rate_port1_c0 * (inspector_choice * value_c * c_Q +
border_treatment_cost * (1 - inspector_choice) * c_Q + fine)))
 let cost_c_0_2 (c_port2_cost + (s_rate_port2_c0 * (inspector_choice * value_c * c_Q +
border_treatment_cost * (1 - inspector_choice) * c_Q + fine)))
 set cost_c cost_c_0_1 set c_port 1 set choice_c 0 set s_rate_port1_c  s_rate_port1_c0 set
pretreat_s_c pretreat_s_c0
 if (cost_c > cost_c_0_2) [set cost_c cost_c_0_2 set choice_c 0 set c_port 2 set s_rate_port2_c
s_rate_port2_c0 set pretreat_s_c pretreat_s_c0 ]

;**FOR FIRM C WITH LEVEL 1 PRETREATMENT TO PORT 1 AND 2**
 set pre_choice_c pretreatment_effectiveness1
 set choice_c1 0.4
 set pretreat_s_c1 0
 set s_rate_port1_c1  0
 set s_rate_port2_c1  0

 ;pretreatment success
```

```
 if (random 100 > (pre_choice_c * choice_c1)) [set pretreat_s_c1 1]

;inspection calculation
set port1_c_v (port1_c_violations / 2)
set port2_c_v (port2_c_violations / 2)

set in_rate_port1_c (base_rate_of_in_port1 + (additional_violation_port1 * port1_c_v))
   if (in_rate_port1_c > 100) [set in_rate_port1_c 100]
set in_rate_port2_c (base_rate_of_in_port2 + (additional_violation_port2 * port2_c_v))
    if (in_rate_port2_c > 100) [set in_rate_port2_c 100]

;success of inspection
 set in_s_rate_port1_c1 (in_base_s_rate_port1 * in_rate_port1_c * c_infected * pretreat_s_c1)
    if (in_s_rate_port1_c1 > random 100) [set s_rate_port1_c1 1]
 set in_s_rate_port2_c1 (in_base_s_rate_port2 * in_rate_port2_c * c_infected * pretreat_s_c1)
    if (in_s_rate_port2_c1 > random 100) [set s_rate_port2_c1 1]

;cost calculation
let cost_c_1_1 ((pretreat_level1_c * pre_cost1) + c_port1_cost + (s_rate_port1_c1 *
(inspector_choice * value_c * c_Q + border_treatment_cost *
           (1 - inspector_choice) * c_Q + fine)))
let cost_c_1_2 ((pretreat_level1_c * pre_cost1) + c_port2_cost + (s_rate_port2_c1 *
(inspector_choice * value_c * c_Q + border_treatment_cost *
           (1 - inspector_choice) * c_Q + fine)))
 if (cost_c > cost_c_1_1) [set cost_c cost_c_1_1 set choice_c 1 set c_port 1 set s_rate_port1_c
s_rate_port1_c1 set pretreat_s_c pretreat_s_c1]
 if (cost_c > cost_c_1_2) [set cost_c cost_c_1_2 set choice_c 1 set c_port 2 set s_rate_port2_c
s_rate_port2_c1 set pretreat_s_c pretreat_s_c1]

;**FOR FIRM C WITH LEVEL 2 PRETREATMENT TO PORT 1 AND 2**
  set pre_choice_c pretreatment_effectiveness2
  set choice_c2 0.65
  set pretreat_s_c2 0
  set s_rate_port1_c2  0
  set s_rate_port2_c2  0

 ;pretreatment success
 if (random 100 > (pre_choice_c * choice_c2)) [set pretreat_s_c2 1]

;inspection calculation
set port1_c_v (port1_c_violations / 2)
set port2_c_v (port2_c_violations / 2)

set in_rate_port1_c (base_rate_of_in_port1 + (additional_violation_port1 * port1_c_v))
   if (in_rate_port1_c > 100) [set in_rate_port1_c 100]
set in_rate_port2_c (base_rate_of_in_port2 + (additional_violation_port2 * port2_c_v))
    if (in_rate_port2_c > 100) [set in_rate_port2_c 100]

;success of inspection
 set in_s_rate_port1_c2 (in_base_s_rate_port1 * in_rate_port1_c * c_infected * pretreat_s_c2)
    if (in_s_rate_port1_c2 > random 100) [set s_rate_port1_c2 1]
 set in_s_rate_port2_c2 (in_base_s_rate_port2 * in_rate_port2_c * c_infected * pretreat_s_c2)
    if (in_s_rate_port2_c2 > random 100) [set s_rate_port2_c2 1]

;cost calculation
```

```
let cost_c_2_1 ((pretreat_level2_c * pre_cost2) + c_port1_cost + (s_rate_port1_c2 *
(inspector_choice * value_c * c_Q + border_treatment_cost *
           (1 - inspector_choice) * c_Q + fine)))
let cost_c_2_2 ((pretreat_level2_c * pre_cost2) + c_port2_cost + (s_rate_port2_c2 *
(inspector_choice * value_c * c_Q + border_treatment_cost *
            (1 - inspector_choice) * c_Q + fine)))
 if (cost_c > cost_c_2_1) [set cost_c cost_c_2_1 set choice_c 2 set c_port 1 set s_rate_port1_c
s_rate_port1_c2 set pretreat_s_c pretreat_s_c2]
 if (cost_c > cost_c_2_2) [set cost_c cost_c_2_2 set choice_c 2 set c_port 2 set s_rate_port2_c
s_rate_port2_c2 set pretreat_s_c pretreat_s_c2]


;**FOR FIRM C WITH LEVEL 3 PRETREATMENT TO PORT 1 AND 2**
  set pre_choice_c pretreatment_effectiveness3
  set choice_c3 1
  set pretreat_s_c3 0
  set s_rate_port1_c3  0
  set s_rate_port2_c3  0

 ;pretreatment success
 if (random 100 > (pre_choice_c * choice_c3)) [set pretreat_s_c3 1]

;inspection calculation
set port1_c_v (port1_c_violations / 2)
set port2_c_v (port2_c_violations / 2)

set in_rate_port1_c (base_rate_of_in_port1 + (additional_violation_port1 * port1_c_v))
   if (in_rate_port1_c > 100) [set in_rate_port1_c 100]
set in_rate_port2_c (base_rate_of_in_port2 + (additional_violation_port2 * port2_c_v))
    if (in_rate_port2_c > 100) [set in_rate_port2_c 100]

;success of inspection
set in_s_rate_port1_c3 (in_base_s_rate_port1 * in_rate_port1_c * c_infected * pretreat_s_c3)
    if (in_s_rate_port1_c3 > random 100) [set s_rate_port1_c3 1]
 set in_s_rate_port2_c3 (in_base_s_rate_port2 * in_rate_port2_c * c_infected * pretreat_s_c3)
    if (in_s_rate_port2_c3 > random 100) [set s_rate_port2_c3 1]

;cost calculation
let cost_c_3_1 ((pretreat_level3_c * pre_cost3) + c_port1_cost + (s_rate_port1_c3 *
(inspector_choice * value_c * c_Q + border_treatment_cost *
           (1 - inspector_choice) * c_Q + fine)))
let cost_c_3_2 ((pretreat_level3_c * pre_cost3) + c_port2_cost + (s_rate_port2_c3 *
(inspector_choice * value_c * c_Q + border_treatment_cost *
            (1 - inspector_choice) * c_Q + fine)))
 if (cost_c > cost_c_3_1) [set cost_c cost_c_3_1 set choice_c 3 set c_port 1 set s_rate_port1_c
s_rate_port1_c3 set pretreat_s_c pretreat_s_c3]
 if (cost_c > cost_c_3_2) [set cost_c cost_c_3_2 set choice_c 3 set c_port 2 set s_rate_port2_c
s_rate_port2_c3 set pretreat_s_c pretreat_s_c3]

set c_cost  cost_c
set c_choice choice_c
set c_s_rate_port1 s_rate_port1_c
set c_s_rate_port2 s_rate_port2_c
set c_pretreat_s pretreat_s_c

; violation count by port for firm c
```

```
if (s_rate_port1_c0 = 1) and (c_choice = 0) and (c_port = 1) [set port1_c_violations
(port1_c_violations + 1)]
if (s_rate_port1_c1 = 1) and (c_choice = 0.4) and (c_port = 1) [set port1_c_violations
(port1_c_violations + 1)]
if (s_rate_port1_c2 = 1) and (c_choice = 0.65) and (c_port = 1) [set port1_c_violations
(port1_c_violations + 1)]
if (s_rate_port1_c3 = 1) and (c_choice = 1) and (c_port = 1) [set port1_c_violations
(port1_c_violations + 1)]

if (s_rate_port2_c0 = 1) and (c_choice = 0) and (c_port = 2) [set port2_c_violations
(port2_c_violations + 1)]
if (s_rate_port2_c1 = 1) and (c_choice = 0.4) and (c_port = 2) [set port2_c_violations
(port2_c_violations + 1)]
if (s_rate_port2_c2 = 1) and (c_choice = 0.65) and (c_port = 2) [set port2_c_violations
(port2_c_violations + 1)]
if (s_rate_port2_c3 = 1) and (c_choice = 1) and (c_port = 2) [set port2_c_violations
(port2_c_violations + 1)]

 ;////////////////////////////
 ; ENTITY ACTION
 ;////////////////////////////
 let a pest_per_truck
 while [a > -1] [
   if (a_infected = 1) and (a_pretreat_s = 1) and (a_s_rate_port1 = 0) and (a_port = 1)  [pest_a1-
creation]
   if (a_infected = 1) and (a_pretreat_s = 1) and (a_s_rate_port2 = 0) and (a_port = 2)  [pest_a2-
creation]

   if (b_infected = 1) and (b_pretreat_s = 1) and (b_s_rate_port1 = 0) and (b_port = 1)  [pest_b1-
creation]
   if (b_infected = 1) and (b_pretreat_s = 1) and (b_s_rate_port2 = 0) and (b_port = 2)  [pest_b2-
creation]

   if (c_infected = 1) and (c_pretreat_s = 1) and (c_s_rate_port1 = 0) and (c_port = 1)  [pest_c1-
creation]
   if (c_infected = 1) and (c_pretreat_s = 1) and (c_s_rate_port2 = 0) and (c_port = 2)  [pest_c2-
creation]

   set a (a - 1)
 ]


 move-pests

 pest-age
 ;////////////////////////////

 ;////////////////////////////
 ; TIME INCREMENT
 ;////////////////////////////
 set time ( time + 1)
 if (time mod timesteps_per_week = 0) [set week ( week + 2 )]
 ;////////////////////////////

 ;////////////////////////////
```

```
 ; PLOTS
 ;////////////////////////////
 do-plots
 ;////////////////////////////

 ;////////////////////////////
 ; Establishment Probability
 ;////////////////////////////
 establishment

end
;///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////


;///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
; PEST BEHAVIOR
;///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
to move-pests
 ask pests[
  set age (age + 1)
  if ((crop_ready = 1) and (not (pcolor = 15.8)) and (random 100 < establishment_prob)) [set
found_food 1 set reproduce 1 set food 0 set pcolor 15.8 set taken 1]
  if (reproduce = 1) [reproduce_p]
  if found_food = 0 [right random 360
            forward pest_movement / kms_to_patches_ratio
            let a 0
            while [ (pcolor < 15) and a < 2 ] [ back pest_movement / kms_to_patches_ratio
right random 360 set a (a + 1)]
            if (pcolor < 15) [die]
           ]
  if (age > 3 and found_food = 0) [die]
 ]
end

to reproduce_p
 let x xcor
 let y ycor
 if (random 100 < establishment_prob) [ ask patch-at -1 -1 [if ((crop_ready = 1) and (taken = 0))
[sprout-pest-children 1 []] set taken 1]]
 if (random 100 < establishment_prob) [ ask patch-at -1 0 [if ((crop_ready = 1) and (taken = 0))
[sprout-pest-children 1 []] set taken 1]]
 if (random 100 < establishment_prob) [ ask patch-at -1 1 [if ((crop_ready = 1) and (taken = 0))
[sprout-pest-children 1 []] set taken 1]]
 if (random 100 < establishment_prob) [ ask patch-at 0 1 [if ((crop_ready = 1) and (taken = 0))
[sprout-pest-children 1 []] set taken 1]]
 if (random 100 < establishment_prob) [ ask patch-at 0 -1 [if ((crop_ready = 1) and (taken = 0))
[sprout-pest-children 1 []] set taken 1]]
 if (random 100 < establishment_prob) [ ask patch-at 1 -1 [if ((crop_ready = 1) and (taken = 0))
[sprout-pest-children 1 []] set taken 1]]
 if (random 100 < establishment_prob) [ ask patch-at 1 0 [if ((crop_ready = 1) and (taken = 0))
[sprout-pest-children 1 []] set taken 1]]
 if (random 100 < establishment_prob) [ ask patch-at 1 1 [if ((crop_ready = 1) and (taken = 0))
[sprout-pest-children 1 []] set taken 1]]
end

to pest-age
```

```
 ask pest-children [hatch-pests 1 [set color red set shape "bug" set size 5 set found_food 1 set
reproduce 1 set age 0] die]
end
;/////////////////////////////////////////////////////////////////////////////////////////////////////////////////


;/////////////////////////////////////////////////////////////////////////////////////////////////////////////////
; ENTITY CREATION
;/////////////////////////////////////////////////////////////////////////////////////////////////////////////////
to pest_a1-creation
 let destination 0
 set destination random 100
 if (destination <= 5)[ask patch-at (35 + random 53) (-117 + random 40) [sprout-pests 1 [set
found_food 0 set reproduce 0 set age 0]]]
 if (destination > 5 and destination <= 8)[ask patch-at (111 + random 26) (-125 + random 30)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 8 and destination <= 13)[ask patch-at (150 + random 26) (-180 + random 50)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 13 and destination <= 16)[ask patch-at (200 + random 30) (-125 + random 22)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 16 and destination <= 30)[ask patch-at (-117 + random 73) (37 + random 80)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 30 and destination <= 44)[ask patch-at (-165 + random 46) (127 + random 58)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 44 and destination <= 51)[ask patch-at (-134 + random 67) (-42 + random 35)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 51 and destination <= 57)[ask patch-at (-163 + random 40) (35 + random 36)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 57 and destination <= 63)[ask patch-at (-54 + random 35) (-75 + random 19)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 63 and destination <= 69)[ask patch-at (-196 + random 27) (104 + random 30)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 59 and destination <= 75)[ask patch-at (-190 + random 45) (75 + random 28)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
end

to pest_a2-creation
 let destination 0
 set destination random 100
 if (destination <= 5)[ask patch-at (35 + random 53) (-117 + random 40) [sprout-pests 1 [set
found_food 0 set reproduce 0 set age 0]]]
 if (destination > 5 and destination <= 8)[ask patch-at (111 + random 26) (-125 + random 30)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 8 and destination <= 13)[ask patch-at (150 + random 26) (-180 + random 50)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 13 and destination <= 16)[ask patch-at (200 + random 30) (-125 + random 22)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 16 and destination <= 30)[ask patch-at (-117 + random 73) (37 + random 80)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 30 and destination <= 44)[ask patch-at (-165 + random 46) (127 + random 58)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 44 and destination <= 51)[ask patch-at (-134 + random 67) (-42 + random 35)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 51 and destination <= 57)[ask patch-at (-163 + random 40) (35 + random 36)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
```

```
  if (destination > 57 and destination <= 63)[ask patch-at (-54 + random 35) (-75 + random 19)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 63 and destination <= 69)[ask patch-at (-196 + random 27) (104 + random 30)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 59 and destination <= 75)[ask patch-at (-190 + random 45) (75 + random 28)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
end

to pest_b1-creation
  let destination 0
  set destination random 100
  if (destination <= 5)[ask patch-at (35 + random 53) (-117 + random 40) [sprout-pests 1 [set
found_food 0 set reproduce 0 set age 0]]]
  if (destination > 5 and destination <= 8)[ask patch-at (111 + random 26) (-125 + random 30)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 8 and destination <= 13)[ask patch-at (150 + random 26) (-180 + random 50)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 13 and destination <= 16)[ask patch-at (200 + random 30) (-125 + random 22)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 16 and destination <= 30)[ask patch-at (-117 + random 73) (37 + random 80)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 30 and destination <= 44)[ask patch-at (-165 + random 46) (127 + random 58)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 44 and destination <= 51)[ask patch-at (-134 + random 67) (-42 + random 35)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 51 and destination <= 57)[ask patch-at (-163 + random 40) (35 + random 36)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 57 and destination <= 63)[ask patch-at (-54 + random 35) (-75 + random 19)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 63 and destination <= 69)[ask patch-at (-196 + random 27) (104 + random 30)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 59 and destination <= 75)[ask patch-at (-190 + random 45) (75 + random 28)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
end

to pest_b2-creation
  let destination 0
  set destination random 100
  if (destination <= 5)[ask patch-at (35 + random 53) (-117 + random 40) [sprout-pests 1 [set
found_food 0 set reproduce 0 set age 0]]]
  if (destination > 5 and destination <= 8)[ask patch-at (111 + random 26) (-125 + random 30)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 8 and destination <= 13)[ask patch-at (150 + random 26) (-180 + random 50)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 13 and destination <= 16)[ask patch-at (200 + random 30) (-125 + random 22)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 16 and destination <= 30)[ask patch-at (-117 + random 73) (37 + random 80)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 30 and destination <= 44)[ask patch-at (-165 + random 46) (127 + random 58)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 44 and destination <= 51)[ask patch-at (-134 + random 67) (-42 + random 35)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 51 and destination <= 57)[ask patch-at (-163 + random 40) (35 + random 36)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
  if (destination > 57 and destination <= 63)[ask patch-at (-54 + random 35) (-75 + random 19)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
```

```
 if (destination > 63 and destination <= 69)[ask patch-at (-196 + random 27) (104 + random 30)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 59 and destination <= 75)[ask patch-at (-190 + random 45) (75 + random 28)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
end

to pest_c1-creation
 let destination 0
 set destination random 100
 if (destination <= 5)[ask patch-at (35 + random 53) (-117 + random 40) [sprout-pests 1 [set
found_food 0 set reproduce 0 set age 0]]]
 if (destination > 5 and destination <= 8)[ask patch-at (111 + random 26) (-125 + random 30)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 8 and destination <= 13)[ask patch-at (150 + random 26) (-180 + random 50)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 13 and destination <= 16)[ask patch-at (200 + random 30) (-125 + random 22)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 16 and destination <= 30)[ask patch-at (-117 + random 73) (37 + random 80)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 30 and destination <= 44)[ask patch-at (-165 + random 46) (127 + random 58)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 44 and destination <= 51)[ask patch-at (-134 + random 67) (-42 + random 35)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 51 and destination <= 57)[ask patch-at (-163 + random 40) (35 + random 36)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 57 and destination <= 63)[ask patch-at (-54 + random 35) (-75 + random 19)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 63 and destination <= 69)[ask patch-at (-196 + random 27) (104 + random 30)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 59 and destination <= 75)[ask patch-at (-190 + random 45) (75 + random 28)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
end

to pest_c2-creation
 let destination 0
 set destination random 100
 if (destination <= 5)[ask patch-at (35 + random 53) (-117 + random 40) [sprout-pests 1 [set
found_food 0 set reproduce 0 set age 0]]]
 if (destination > 5 and destination <= 8)[ask patch-at (111 + random 26) (-125 + random 30)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 8 and destination <= 13)[ask patch-at (150 + random 26) (-180 + random 50)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 13 and destination <= 16)[ask patch-at (200 + random 30) (-125 + random 22)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 16 and destination <= 30)[ask patch-at (-117 + random 73) (37 + random 80)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 30 and destination <= 44)[ask patch-at (-165 + random 46) (127 + random 58)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 44 and destination <= 51)[ask patch-at (-134 + random 67) (-42 + random 35)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 51 and destination <= 57)[ask patch-at (-163 + random 40) (35 + random 36)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 57 and destination <= 63)[ask patch-at (-54 + random 35) (-75 + random 19)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
 if (destination > 63 and destination <= 69)[ask patch-at (-196 + random 27) (104 + random 30)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
```

```
 if (destination > 59 and destination <= 75)[ask patch-at (-190 + random 45) (75 + random 28)
[sprout-pests 1 [set found_food 0 set reproduce 0 set age 0]]]
end

;///////////////////////////////////////////////////////////////////////////////////////////////////////////


;///////////////////////////////////////////////////////////////////////////////////////////////////////////
; GRAPHS
;///////////////////////////////////////////////////////////////////////////////////////////////////////////
to do-plots
 set-current-plot "Crop Damage"
 set-current-plot-pen "damage"
   plot (((crop_count - current_crop_count) / crop_count) * 100)
  set cost 599436000 * ((crop_count - current_crop_count)/ crop_count)
  set damage cost / 599436000
  ;$599,436,000 is the value of broccoli production in 2006set-current-plot "pest-pop"
  set-current-plot "pest-pop"
  set-current-plot-pen "pop"
   plot count (pests)


 set-current-plot "Violations of Firm C Port 1"
  set-current-plot-pen "violations"
  plot port1_c_violations


 set-current-plot "Violations of Firm C Port 2"
  set-current-plot-pen "violations"
  plot port2_c_violations


  set-current-plot "Firm C Cost"
  set-current-plot-pen "cost"
   plot c_cost
  set-current-plot "Pretreatment Firm C"
  set-current-plot-pen "pretreatment"
   plot c_choice
   set-current-plot "Port Choice"
   set-current-plot-pen "port 1"
   set-current-plot-pen "port 2"
   plot c_port

  set-current-plot "S1"
  set-current-plot-pen "s1"
  plot c_s_rate_port1

  set-current-plot "S2"
  set-current-plot-pen "s2"
  plot c_s_rate_port2

  set-current-plot "I1"
  set-current-plot-pen "i1"
  plot in_rate_port1_c

  set-current-plot "Did Pretreatment Fail?"
```

```
 set-current-plot-pen "pi"
 plot c_pretreat_s

 set-current-plot "infected"
 set-current-plot-pen "bi"
 plot c_infected

end
;///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////


;///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
; Map setup
;///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
to map_setup
  ; set densities for regions (this picks out patch in map and brands them with their region code and
crop densities)
  ; note regions codes: (north)centralcoast 1, (south)centralcoast 2, (west)southcoast 3,
(east)southcoast 4,
  ;                (north)sanjoaq 5, (south)sanjoaq 6, (west)imperial 7, (east)imperial 8, non-use 0
  ask patches [ set establishment_prob 0
            ifelse (pcolor != 61.8) [set region 10]
           [ifelse (pcolor = 61.8) and (pycor > 120) and (pycor + 1 * pxcor > -40 ) [set food
(food_per_patch * sanjoaq) set region 5 set food_org food set crop_ready 1 set taken 0]
           [ifelse (pcolor = 61.8) and (pycor > 0 and pycor < 120) and (pycor + 1 * pxcor > -40 )
[set food (food_per_patch * sanjoaq) set region 6 set food_org food set crop_ready 1 set taken 0]
           [ifelse (pcolor = 61.8) and (pycor < -80) and (pxcor < 145)  [set food (food_per_patch *
imperial) set region 7 set food_org food set crop_ready 1 set taken 0]
           [ifelse (pcolor = 61.8) and (pycor < -80) [set food (food_per_patch * imperial) set region
8 set food_org food set crop_ready 1 set taken 0]
           [ifelse (pcolor = 61.8) and (pxcor < -60) and (pycor < 0) and ( pycor > -80 ) and (pycor +
1 * pxcor < -40 ) [set food (food_per_patch * southcoast) set region 3 set food_org food set
crop_ready 1 set taken 0]
           [ifelse (pcolor = 61.8) and (pycor < 0) and (pxcor > -60) and ( pycor > -80 ) and (pycor +
1 * pxcor < -40 ) [set food (food_per_patch * southcoast) set region 4 set food_org food set
crop_ready 1 set taken 0]
           [ifelse (pcolor = 61.8) and (pycor > 90) and (pycor + 1 * pxcor < -40 ) [set food
(food_per_patch * centralcoast) set region 1 set food_org food set crop_ready 1 set taken 0]
           [if (pcolor = 61.8) and (pycor > 0 and pycor <= 90) and (pycor + 1 * pxcor < -40 ) [set
food (food_per_patch * centralcoast) set region 2 set food_org food set crop_ready 1 set taken 0]
                  ]
                 ]
                ]
               ]
              ]
             ]
            ]
           ]
           ]
end
;///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////


;///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
; Map reset subroutine
;///////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
```

```
to reset_map
 set week 0
 ask pests [die]
 ask pest-children[die]
 ask patches [  set establishment_prob 0
          ifelse (region = 10) [set region 10 set taken 0]
        [ifelse (region = 5) [set food (food_per_patch * sanjoaq) set region 5 set food_org food set
crop_ready 1 set pcolor 61.8 set taken 0]
        [ifelse (region = 6) [set food (food_per_patch * sanjoaq) set region 6 set food_org food set
crop_ready 1 set pcolor 61.8 set taken 0]
        [ifelse (region = 7) [set food (food_per_patch * imperial) set region 7 set food_org food
set crop_ready 1 set pcolor 61.8 set taken 0]
        [ifelse (region = 8) [set food (food_per_patch * imperial) set region 8 set food_org food
set crop_ready 1 set pcolor 61.8 set taken 0]
        [ifelse (region = 3) [set food (food_per_patch * southcoast) set region 3 set food_org food
set crop_ready 1 set pcolor 61.8 set taken 0]
        [ifelse (region = 4) [set food (food_per_patch * southcoast) set region 4 set food_org food
set crop_ready 1 set pcolor 61.8 set taken 0]
        [ifelse (region = 1) [set food (food_per_patch * centralcoast) set region 1 set food_org
food set crop_ready 1 set pcolor 61.8 set taken 0]
        [if    (region = 2) [set food (food_per_patch * centralcoast) set region 2 set food_org food
set crop_ready 1 set pcolor 61.8 set taken 0]
              ]
             ]
            ]
           ]
          ]
         ]
        ]
       ]
      ]
end
;///////////////////////////////////////////////////////////////////////////////////////////////////////////////////


;///////////////////////////////////////////////////////////////////////////////////////////////////////////////////
; ESTABLISHMENT SUBROUTINE
;///////////////////////////////////////////////////////////////////////////////////////////////////////////////////
to establishment
ifelse week = 24 [ ask patches [set establishment_prob 0 ]]
  [
   if week = 4 [ ask patches [
             ifelse region = 10 []
             [
             ifelse region = 1 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
             [
             ifelse region = 2 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
             [
             ifelse region = 3 [set establishment_prob (80 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
             [
```

```
            ifelse region = 4 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 5 [set establishment_prob (40 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 6 [set establishment_prob (40 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 7 [set establishment_prob (80 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            if region = 8 [set establishment_prob (80 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            ]
            ]
            ]
            ]
            ]
            ]
            ]
            ]
           ]
          ]
  if week = 8 [ ask patches [
            ifelse region = 10 []
            [
            ifelse region = 1 [set establishment_prob (80 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 2 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 3 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 4 [set establishment_prob (40 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 5 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 6 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
```

```
            ifelse region = 7 [set establishment_prob (40 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            if region = 8 [set establishment_prob (20 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            ]
            ]
            ]
            ]
            ]
            ]
            ]
            ]
           ]
         ]
  if week = 12 [ask patches [
            ifelse region = 10 []
            [
            ifelse region = 1 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 2 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 3 [set establishment_prob (40 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 4 [set establishment_prob (20 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 5 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 6 [set establishment_prob (80 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 7 [set establishment_prob (20 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            if region = 8 [set establishment_prob (0 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            ]
            ]
            ]
            ]
            ]
```

```
            ]
            ]
            ]
           ]
        ]
  if week = 16 [ ask patches [
            ifelse region = 10 []
            [
            ifelse region = 1 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 2 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 3 [set establishment_prob (40 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 4 [set establishment_prob (0 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 5 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 6 [set establishment_prob (60 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 7 [set establishment_prob (0 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            if region = 8 [set establishment_prob (0 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            ]
            ]
            ]
            ]
            ]
            ]
            ]
            ]
           ]
        ]
  if week = 20 [ ask patches [
            ifelse region = 10 []
            [
            ifelse region = 1 [set establishment_prob (20 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
```

```
            ifelse region = 2 [set establishment_prob (40 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 3 [set establishment_prob (20 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 4 [set establishment_prob (0 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 5 [set establishment_prob (40 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 6 [set establishment_prob (40 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            ifelse region = 7 [set establishment_prob (0 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            [
            if region = 8 [set establishment_prob (0 + establishment_modifier) if
establishment_prob < 0 [set establishment_prob 0] if establishment_prob > 100 [set
establishment_prob 100]]
            ]
            ]
            ]
            ]
            ]
            ]
            ]
            ]
           ]
         ]
 ]
 end
;////////////////////////////////////////////////////////////////////////////////////////////////////////////////////


;////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
; Establishment Probablility preview
;////////////////////////////////////////////////////////////////////////////////////////////////////////////////////
to preview
 go
 ask patches [if region != 10 [ if establishment_prob < 20 [set pcolor yellow]
           if establishment_prob >= 20 and establishment_prob < 40[set pcolor green]
           if establishment_prob >= 40 and establishment_prob < 60 [set pcolor blue]
           if establishment_prob >= 60 and establishment_prob < 80 [set pcolor magenta]
           if establishment_prob >= 80 [set pcolor red]
          ]
        ]
 end
;//////////////////////////////////////////////////////////
```