Modeling the Role of Carrier Species in the Spread of Hemlock Woolly Adelgid

Lawton J. Clites
The Mitre Corporation

Zoe Henscheid
Northrop Grumman Mission Systems

INTRODUCTION

The hemlock woolly adelgid (HWA), an aphid-like insect native to Asia, was first observed in the eastern United States in Richmond, Virginia, in 1951. Since then it has spread to 16 states from Maine to Georgia and poses a serious threat to the future existence of eastern and Carolina hemlock (*Tsuga canadensis* and *Tsuga caroliniana*, respectively) in the region. To study this problem, and to create an illustrative example of how data farming techniques can be applied to environmental issues, we created a series of model scenarios using the Pythagoras distillation to simulate the spread of this invasive species--focusing primarily on the role of carrier species in the dispersal of HWA. Since this issue may be unfamiliar to many members of the Project Albert community, a slightly more in-depth background to the problem and players therein is included in this paper.

1. BACKGROUND

1.1 Hemlocks

Hemlocks (*Tsuga* spp.) belong to the pine family (*Pinaceae*) and are native to North America and Asia. They are not, as commonly mistaken, related to the plant used by Socrates to commit suicide [1]. Of the seven hemlock species, *Tsuga sieboldii*, *T. chinensis*, and *T. diversifolia* are native to East Asia, while four species are native to North America. Two of those, *T. merensiana* and *T. heterophylla,* can be found along the West Coast from central California to Alaska. Eastern or Canadian hemlock, *T. canadensis*, ranges from Alabama to Southeastern Canada and the Great Lake states, while the Carolina hemlock, *T. caroliniana*, a close relative of the eastern hemlock, is limited to the Appalachian region from Virginia and West Virginia through the Carolinas and Tennessee to Georgia. Of all the hemlock species, eastern and Carolina hemlocks are the most susceptible to the hemlock woolly adelgid and are therefore the species focused upon in this study.

Eastern hemlocks can live in excess of 800 years and require 250-300 years to mature. These trees regularly reach heights of up to 30m; however they have been documented at heights of over 50m. Eastern hemlocks have short needles occurring in rows on either side of the branch plus a row lying underside-up flattened along the top of the branch. They prefer cool, moist habitat and as such are found at increasing elevations moving southward through their range, from sea level to 730m in the North and Northeast, 300-910m in the Allegheny Plateau, and 610-1520m in the southern Appalachians. Eastern hemlock is the most shade tolerant tree species in the eastern U.S. forest [2] and can survive under suppression with as little as 5% of the full sunlight for up to 400 years. It commonly grows on shady slopes, in valleys, and near surface water.

The Carolina hemlock is usually smaller (up to 15m in height) with similar cones and needles protruding in a less organized fashion from the branch. It can occasionally be observed in moist areas [3], but is more common on sunny rocky slopes. Both species prefer acidic soils.

Hemlocks were previously cut for their lumber, which was prized for use in railroad ties. The lumber was also used for light framing, while the inner bark was used in the leather tanning process. With the decline in new railroad construction and the increased use of synthetic chemicals in leather production (and since hemlock wood is considered to be of "poor quality" [4]), hemlocks are currently timbered predominately for pulp. Both species are cultivated for ornament.

Hemlocks play a valuable roll in the natural environment where they serve as browse and cover for a number of animal species. They also provide shade along streams, keeping water temperatures low, and are therefore important to cold-water fish such as trout.

Hemlocks are very susceptible to drought, particularly before they reach maturity. The hemlock's thick bark provides older trees with good protection from small fires. High intensity fires, however, are particularly dangerous to hemlocks because their roots can be damaged by the combustion of the thick litter layer that typically accumulates on the ground below them. Hemlocks can also suffer from wind throw, especially in areas that have been logged, and eastern hemlock is one of the eastern tree species most likely to be struck by lightning [5]. In addition to the hemlock woolly adelgid, a variety of organisms pose a threat to hemlocks, including molds, root rots, insects, and browsing mammals.

1.2 Hemlock Woolly Adelgid

The Hemlock Woolly Adelgid, *Adelges tsugae* Annand (Homoptera: Adelgidae), is a native of east Asia (China, Japan, and Taiwan) where it feeds on hemlock species but causes little damage, assumedly because of both natural resistance among the native hemlocks and because of control by predator species. It has been found in western North America (first observed in 1924) where it also causes little damage, and in eastern North America (first observed in 1951) where it has become a serious pest. A relative of aphids, it feeds on sap from young branches, resulting in premature needle drop, impeded tree growth, death of branches, and weakened, disfigured, and dead trees [6].

As an insect, HWA begins as an egg, which then hatches into a "crawler" phase. Eggs and crawlers can travel over 1km on wind or foot, and crawlers have the peculiar habit of climbing onto birds and mammals, upon which they can travel an unknown maximum distance [7]. Because the crawlers are so small (approximately 0.3mm [8]), and because they can survive without food for up to two weeks, this distance could conceivably be quite large. Once the crawler finds a suitable location it inserts its mouthparts into a young shoot at the base of a needle. At this point the adelgid becomes stationary and produces a “woolly” excretion (Figure 1). HWA also appears as a winged morph, which in Asia migrates to a spruce species and undergoes sexual reproduction. Due to the absence of a suitable spruce species in the eastern U.S., however, these morphs are thought to die off. Therefore, HWA reproduction in the eastern U.S. is limited to parthenogenesis (asexual reproduction resulting in only females). This means that eastern U.S. HWA populations should, theoretically, have very little genetic variation from which to develop immunity to chemical or biological controls [9].

Figure 1. A hemlock branch infested with HWA (Courtesy of USDA Forest Service).

2. BASE SCENARIO

This section describes the base scenario used to model the spread of HWA in the eastern United States.

2.1 Pythagoras

We chose to use the Pythagoras distillation (version 1.7.4) for this model scenario for a number of reasons, primarily because of its flexibility and available detail concerning sidedness properties and movement and engagement desires.

2.2 Terrain

The base terrain for this scenario represents the physical space of an eastern deciduous forest (green). Features include two mountains/mountain ranges (darker green), which impede movement by 30%, 5 peaks on the mountain features (grey), which impede movement by 80%, and a highway/industrial corridor (black), which impedes movement by 30% (Figure 2). When designing the terrain, we considered creating a more detailed map based on a specific geographic area, but decided that the more simplified terrain originally created had the desired effect on the scenario and did not confine the applicability of the scenario to a specific area. This was important because our study was not meant to be an experimental history study, but a look at the spread - past, present, and future - of HWA throughout the eastern United States.

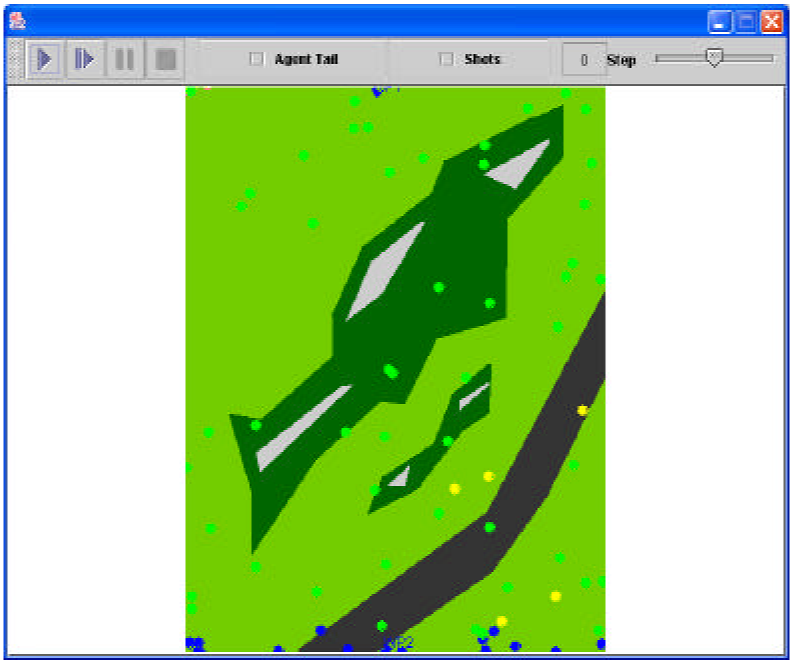

Figure 2. Initial conditions for hemlock base scenario in Pythagoras window.

2.3 Agents

There are three agent classes in the base scenario representing hemlocks (green), initially infected hemlocks (yellow), and birds (blue). The hemlocks are stationary and instantiate with a random distribution throughout the study area (including features) at an instance of 50. Each agent may be viewed as representing a single tree or a stand of trees, the latter being preferred for reasons discussed later in the paper.

The initially infected hemlocks are also stationary and instantiate, at an instance of 5, with a random distribution within 150 pixels of a point in the lower right quadrant of the study area. They too may be viewed as representing either individual infected trees or a stand of trees.

Fifteen bird agents (representing a carrier species) instantiate along the lower perimeter of the study area before beginning their "migration" between a pair of waypoints, one each at the top and bottom of the study area. The bird agents complete this roundtrip journey approximately once every 100 time steps, setting the time scale of 100 time steps approximating one year (the 1000 time steps of a run represent approximately 10 years). During their migrations, the bird agents have a desire to “flock” (move towards each other if more than 20 pixels apart and away from each other if less than 10 pixels apart) and to move randomly. They also prefer the base terrain to the features, and because of this preference, they tend to move more or less in a diagonally leaning (lower left to upper right) ellipse, generally cutting across the mountain feature at the narrower points near the ends and following the lower side of the industrial corridor feature as they move “north.” Like the hemlock agents, each bird agent may be thought of as representing either one bird or one flock of birds.

As the scenario run progresses, although the bird agents continue to follow approximately the same migratory route, their group becomes more and more separated. The dissipation of the flocking nature of the bird agents over time was of some concern to us. In natural studies, however, numerous bird species have been witnessed carrying HWA, some of which are actually non-migratory. Of the bird species that do migrate, there is a great variety in the timing and routes followed during migration, both between species and sometimes within a species [10]. Since our study is not specifically a study of bird migration, we considered the movement of the bird agents in our model to be an acceptable approximation of reality, even with the loss of temporal formation as the time steps progress.

2.4 Modeling the Spread of HWA

We chose to model the spread of hemlock woolly adelgid using the “paintball” weapons available in Pythagoras. In our scenario, the HWA are represented not as a separate agent but as a color (red), which is transmitted from agent to agent. The yellow of the initially infected hemlocks represents, then, the +255 green of the hemlocks and the +255 red of an HWA infestation. When a bird passes near an infected hemlock the bird becomes purple, simulating it landing on the tree and picking up one or more HWA crawlers. This color change triggers an alternate behavior for the bird, prompting it to fire +255 red at the next uninfected hemlock that is near the bird’s continued migratory route. Simultaneously, in most cases, the bird receives a -255 dose of red from the tree, representing a “trade”—the bird dropping its cargo (HWA) and the hemlock becoming infested. If the bird does not perform this trade within 50 time steps it will revert to its previous behavior and will no longer be infectious, but will remain purple until fired upon by an uninfected hemlock

Upon receiving the +255 red, a tree will enter an intermediate behavior, displaying yellow color (indicating that it has had contact with the HWA) but firing no weapon until the passage of 50 relative time steps. This behavior was designed to approximate the life cycle of the HWA which only reproduces twice a year. After those 50 time steps the now infected hemlock agent will begin firing +255 red at any non-HWA-carrying bird agent that passes within range.

Additionally, after a hemlock agent (either hemlock or initially infected hemlock) begins spreading HWA, the passage of 400 relative time steps (with a 50 time step tolerance) will trigger a behavior and color change in that agent. The color change is positive 255 in all color bands (red, green, and blue), turning the infected hemlocks white and indicating the onset of mortality (Figure 3), which has been observed in the field between 3 and 6 years after introduction of HWA [11]. Agents representing dead trees in this scenario do not continue to spread HWA.

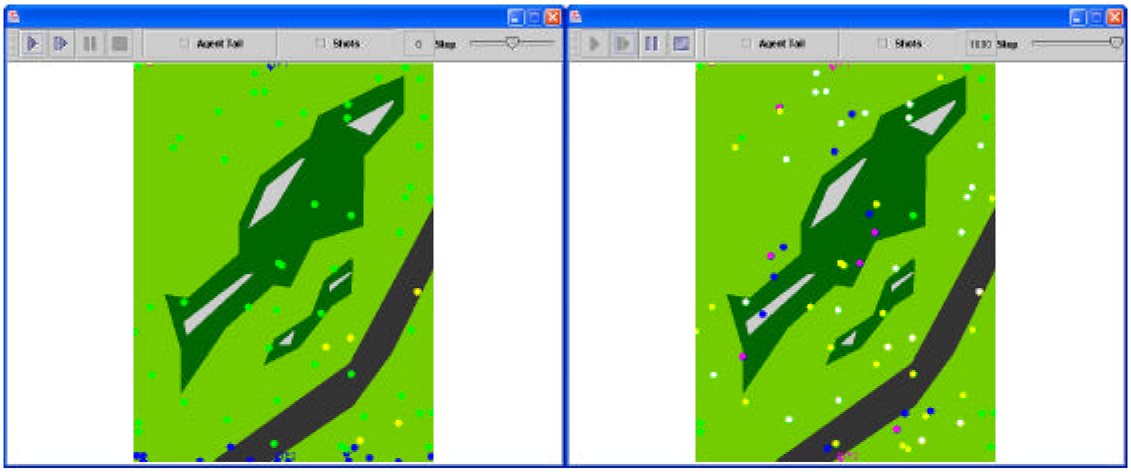

Figure 3. Initial (left) and final (right) conditions for base scenario.

3. CONTROL SCENARIOS

We decided to design two additional scenarios, built from the original base scenario, to model the introduction of a control agent. A number of controls of HWA are currently being either implemented or researched for possible implementation, including natural predators imported from Asia, chemical controls, and entomopathogenic fungi which invade the body of their host and use its resources to reproduce (resulting in mortality of the host) before releasing airborne spores.

In our control scenarios, the basic control agent is invulnerable and targets both infested trees and birds carrying HWA, delivering a -255 red color change and triggering behavior to simulate the death or drop of the HWA. In the "random line" scenario, 6 control agents instantiate in a thin band running left to right through the center of the study area, then move randomly (Figure 4), representing how a control agent such as an entomopathogenic fungus might be introduced along a line before being spread by wind and host movement.

The "stationary perimeter" scenario is identical to the random line scenario, except the control agents do not move from the points where they are instantiated, instead they remain stationary. This scenario could be more representative of the introduction of natural predators along a perimeter or of the repeated application of chemical controls along a line.

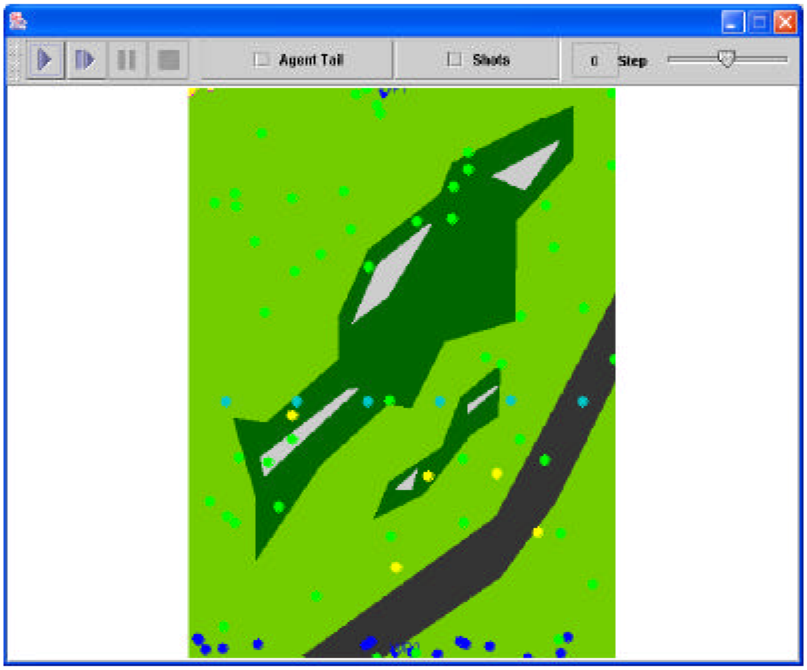

Figure 4. Initial conditions for both control scenarios.

4. MODELING THE EFFECTS OF COLD TEMPERATURES ON HWA

Another factor that may turn out to be a natural control on at least the northerly spread of HWA is cold. Bruce Parker and his team found that a degree of increased mortality of HWA occurs at temperatures of -15C, and total mortality occurs at temperatures of -35C [12]. These temperatures are not unheard of in regions along the northern perimeter of the current HWA range in the eastern United States.

To investigate how this might affect the spread of HWA we designed a model scenario, again based on the original scenario, where terrain features represent geographic regions with progressively lower winter minimum temperatures (Figure 5). Each of the five terrain bands provides a different protection factor (0 in the lower half of the area, then 0.5, 0.9, 0.98, and 1.0 moving towards the top of the study area). Because these protection factors generally prevent the hemlock agents from receiving a full +255 red from birds carrying the pest, a series of cascading alternate behaviors for the hemlocks was established to vary the infectiousness and the time to the onset of mortality with varying levels of red. For example, mortality and spread progressed as usual for those hemlocks with +255 red, while hemlocks with red levels between 0 and +51 would fire no color and not succumb to mortality, etc. Since the protection factors also affect the birds, we decided that birds would only spread HWA if they received a full +255 red.

This particular scenario has not yet been data farmed, but is of interest for possible future study either as it is or with the incorporation of a control agent.

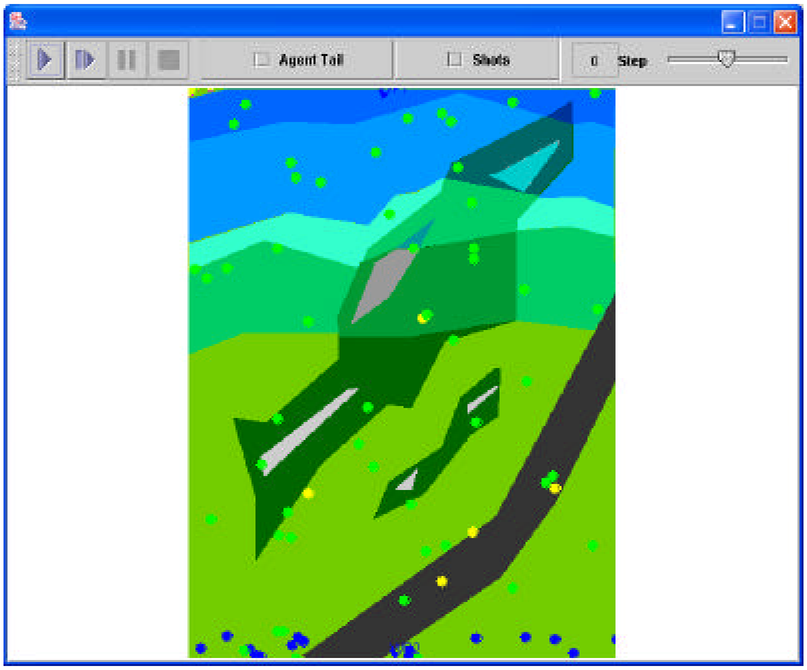

Figure 5. Initial conditions for cold temperature scenario.

5. Measures of Effectiveness (MOEs)

For all scenarios, three collector agents were designed to tally the number of dead hemlocks, the number of infected hemlocks, and the number of birds carrying HWA. Though we could find the data mathematically, we decided that for future runs it would be helpful to have an additional collector agent for tallying the number of uninfected trees.

Of the data collected we limited our analysis to the initial, final, maximum, and/or minimum number of unit members for each of these collector agents, depending on the scenario.

6. DATA FARMING

To decide what parameters to vary and how to interpret the output of those runs, we developed a list of questions we wished to address through data farming. These questions, and the parameters varied, are shown in Table 1.

Table 1. Data farming questions and parameters.

Question	Parameter Varied
How significant is the number of initially infected trees in a region to the spread of the infestation?	Instance of initially infected hemlocks.
How does the density of an initial infestation affect the spread of the infestation?	Proximity of initially infected hemlocks to center point of instantiation.
Is the spread of the infestation greater in forests where hemlocks are more prevalent?	Instance of uninfected hemlocks.
How do environmental conditions (such as drought, presence of other organisms harmful to hemlocks, etc.,) affect the spread of the pest?	Relative time steps between infestation and mortality. (More time steps between infestation and mortality would represent environmental conditions favorable to hemlocks, while a smaller number of time steps would represent more stressful environmental conditions.)
How significant is the number of individuals of a carrier species to the spread of the pest?	Instance of bird agents.
How does the persistence of the pest while on the carrier species affect its spread?	Relative time steps for bird agents to carry the HWA. (Not yet data farmed)
How many control agents need to be released into the environment (compared to trees/infected trees) to eradicate the pest?	Instance of control agents.
How does the geographic relationship between initially infected trees and terrain features affect the spread of the pest?	Initial location of initially infected trees. (Not yet data farmed)

7. RESULTS AND DISCUSSION

7.1 Base Scenario

When analyzing the data collected from our data farming runs, we focused primarily on answering the questions we had formulated prior to submitting the runs at MHPCC. Generally our results corresponded with what we would expect to see in the natural environment and therefore may be considered to validate the model.

Statistical analysis proved rather difficult, both because of differences in scale concerning the ranges of certain parameters and because changing some parameters inherently changed the end conditions (for instance, raising the number of initially infected hemlocks in the base scenario invariably resulted in at least those additional agents being counted as dead at the end of the run). In an attempt to standardize the data, we examined the percent change in hemlock mortality over the percent change in the value of each parameter from the standard conditions used in the original scenario (Table 2). Additionally, when looking at the data concerning changes in the instance of initially infected hemlocks we subtracted the number of initially infected hemlocks from the final number of dead hemlocks, since in the base scenario any initially infected hemlocks would invariably die by the end of the run. When looking at changes in the instance of hemlocks we compared not the total number of dead hemlocks but the percent dead hemlocks (minus 5, representing the mean initially infected hemlocks) over the initial instance of hemlocks, giving a value representing the final number of infected trees from the initial number of healthy trees.

Table 2. A comparison of changes in hemlock mortality relative to changes in parameter values in base scenario.

Parameter	Value	Change in parameter from standard conditions	Hemlock mortality*	Change in hemlock mortality from standard conditions**	Change in hemlock mortality over change parameter
Initially infected hemlocks	1	-0.8	3.279	-0.638	0.798
	3	-0.4	7.510	-0.172	0.430
	5**	0	9.070	0	NA
	7	0.4	10.251	0.130	0.326
	9	0.8	10.367	0.143	0.179
Birds	10	-0.333	14.544	-0.187	0.561
	15**	0	17.890	0	NA
	20	0.333	21.851	0.221	0.664
Proximity to central point for initially infected hemlocks	50	-0.667	9.013	-0.602	0.903
	150**	0	22.630	0	NA
	250	0.667	22.643	0.001	0.001
Relative time-steps to onset of mortality	250	-0.375	21.647	0.185	-0.495
	400**	0	18.260	0	NA
	550	0.375	14.379	-0.213	-0.567
Initially uninfected hemlocks	20	-0.6	38.9%	0.420	-0.700
	50**	0	27.4%	0	NA
	80	0.6	22.2%	-0.190	-0.316

Further complicating the analysis, any trees in the base scenario infected at the end of the run would, if the run continued, inevitably die. Therefore, if one wishes to consider hemlock mortality beyond the simulated 10 years of the run, it is important to also consider the hemlock agents in an infected state at the end of the run (Table 3). Below we have listed the mean number of infected hemlocks at run's end for the collection of parameter values data farmed across and the percent change in infected hemlocks over the percent change in parameter, as well as a combined value called "hemlock casualties" which combines the values for percent change in hemlock mortality and percent change in infected hemlocks over percent change in parameter value.

* Data has been corrected to negate effects of collector agent on final count.
** Denotes the standard conditions in the base scenario.

Table 3. A comparison of changes in infected hemlocks and hemlock casualties relative to changes in parameter values in base scenario.

Parameter	Value	Infected Hemlocks*	Change in infected hemlocks from standard conditions**	Change in infected hemlocks over change in parameter	Change in hemlock casualties over change in parameter
Initially infected hemlocks	1	4.423	-0.571	0.714	1.512
	3	8.283	-0.197	0.492	0.922
	5**	10.311	0	NA	NA
	7	11.04	0.071	0.177	0.502
	9	10.833	0.051	0.063	0.242
Birds	10	7.01	-0.259	0.776	1.337
	15**	9.454	0	NA	NA
	20	10.468	0.107	0.322	0.986
Proximity to central point for initially infected hemlocks	50	6.572	-0.344	0.517	1.419
	150**	10.025	0	NA	NA
	250	10.337	0.031	0.047	0.048
Relative time-steps to onset of mortality	250	4.92	-0.466	1.242	0.748
	400**	9.212	0	NA	NA
	550	12.801	0.390	1.039	0.472
Initially uninfected hemlocks	20	18.69%	0.001	-0.002	-0.701
	50**	18.672%	0	NA	NA
	80	17.324%	-0.072	-0.120	-0.436

We found that, in our base scenario, there was a positive correlation between the number of initially infected hemlocks and hemlock mortality. This appears to be one of the dominant factors in determining the spread of HWA, although the effects appear to taper off near the high end of the range. The instance of initially infected hemlocks also shows a positive correlation with the final number of infected hemlocks at the lower values, however there is in fact a slight decrease between the highest and second highest instances of initially infected hemlocks. The same trend is observed for hemlock casualties.

Another dominant factor appears to be the proximity of the infected hemlocks to the central point about which they instantiate, at least between 50 and 150 pixels, with higher proximity yielding higher hemlock mortality and more infected hemlocks. Upon questioning why this relationship does not continue from 150 pixels and 250 pixels we discovered that 250 pixels would place the agents outside the field of study, so the Pythagoras environment instantiates those agents that would have been outside the area on the perimeter instead. Since the bird agents rarely fly along the edge of the study area,

* Data has been corrected to negate effects of collector agent on final count.
** Denotes the standard conditions in the base scenario.

they rarely pick up the HWA from these initially infected agents. This error on our part, however, still provides us with information. It appears that HWA spread is aided by a more widely distributed group of initially infected hemlocks, but only as long as those hemlocks are still in the path of carrier agents.

We observed that raising the number of hemlocks resulted in an increase in the total number of dead hemlocks and the total number of infected hemlocks, but resulted in a decrease in the percentages of both relative to the initial number of hemlocks. In other words, more trees meant more dead and infected trees at the end of the run, but also more uninfected trees. This was rather surprising, since we expected the spread to be significantly more severe in an area with more potential hosts for the HWA.

One of the most interesting parameters to study was the number of relative time-steps between initial infestation and mortality. In the natural environment, hemlock mortality brought on by HWA can be hastened by other stressors to the hemlocks such as drought or the presence of other parasitic species. In varying this parameter we investigated how the hastened or delayed onset of mortality would affect not individual trees but the spread of HWA through a population. We found that delaying mortality, not surprisingly, resulted in a decrease in overall hemlock mortality and an increase in the number of infected hemlocks, but interestingly, resulted in very little change in the sum of the two (Table 4). It appears that the HWA spread where it would, more or less regardless of how long it took for the hemlock agents to die and cease spreading the infestation.

Table 4. A comparison of hemlock mortality, infected hemlocks, and hemlock casualties at three relative time-step values for the onset of mortality.

Relative time-steps to onset of mortality	Hemlock mortality*	Infected hemlocks*	Hemlock Casualties
250	21.647	4.92	26.6
400	18.26	9.212	27.5
550	14.379	12.801	27.2

When looking at carrier agents in the scenario, we found that an increase in their instance corresponded with an increase in hemlock mortality and in the number of infected hemlocks. Visually, this increase appeared quite negligible, but numerical analysis suggests that it has a greater effect, relative to its change in values, than we had originally suspected.

7.2 Control Scenario

After submitting and beginning the analysis on the data from our first data farming runs we discovered a problem in the scenarios. Near the end of the run our bird agents were running out of color ammunition. We corrected the problem and resubmitted most of the runs, and it is data from those corrected runs that have been discussed so far. One scenario we did not resubmit was the stationary perimeter control scenario. We

* Data has been corrected to negate effects of collector agent on final count.

considered the scenario in which the control agents moved randomly through the study area to be a closer approximation of how a biological control agent might behave, and since biological controls seem to be the more desirable method of control in natural areas we focused on this scenario in our later submissions. In the data from our first submissions, however, we did find that the agents that moved about randomly were more effective in controlling HWA than those that were stationary. Since the ammunition problem should have affected both scenarios similarly, we count this among our observations, though further study would be required to ensure the validity of that observation.

In the corrected submission of the random motion control scenario, we found, as expected, that increasing the instance of control agents resulted in a decrease in both hemlock mortality and infected hemlocks. Within this trend, the data show that returns diminish as control agent instance increases (Figure 6), which is reflective of how a control agent might be expected to behave in a natural environment.

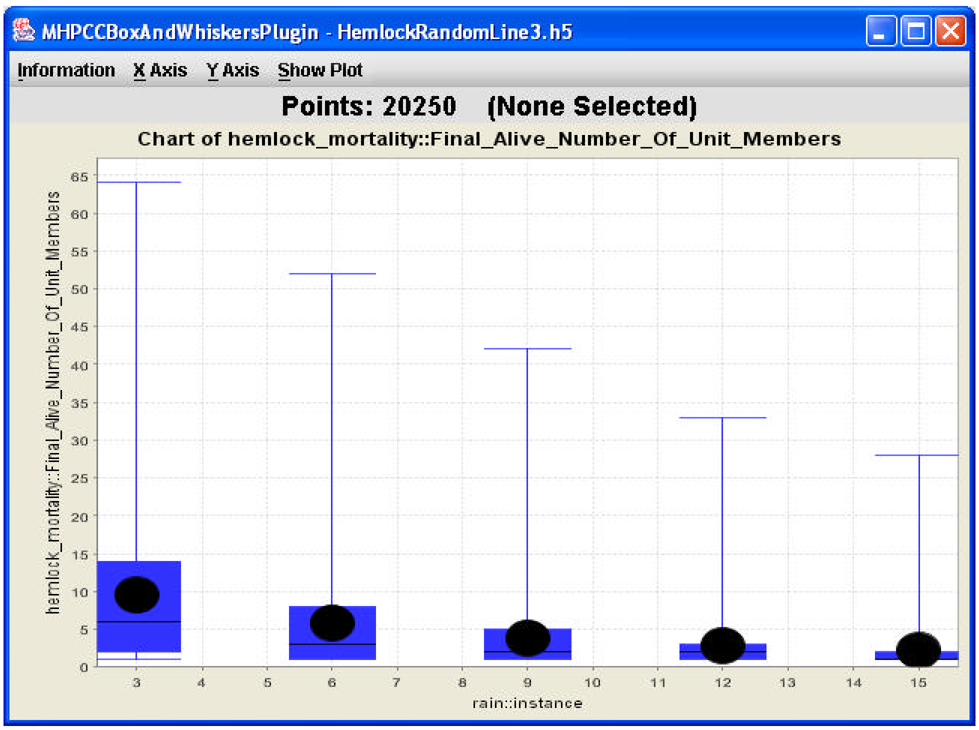

Figure 6. Instance of control agent vs. hemlock mortality (note that the values shown are 1 higher than actual values because of the collector agent.

7.3 Problems Specific to these Scenarios

One problem in the scenario that we ultimately chose to ignore was the lack of tree-to-tree spread of HWA. This is not particularly problematic if one considers each hemlock agent to represent a distinct stand of trees. Since the range of HWA, without the aid of a carrier species, is thought to be just over 1km, it is conceivable that there could be sufficient distance between the stands to prevent the spread of HWA by wind or its own mobility. This may partially explain why the HWA did not spread as quickly as expected in the scenario runs with higher instances of initially uninfected trees, since in a natural environment tree-to-tree spread may play a greater role in areas where hemlocks make up a higher percentage of the forest composition.

On occasion, however, we observed an initially infected tree being uninfected by a nearby, uninfected tree. Since this appeared to be a relatively rare occurrence we decided any adverse effects on the data would not be serious enough to justify the amount of time and effort it would take to correct it, that is, if it could be corrected.

7.4 Applications

This study was meant, to a large extent, to be an illustrative exploration into how data farming techniques can be applied to issues beyond military simulations, and to that end we feel that this study has been a success. We hope also, however, that foresters and biologists working to control the spread of hemlock woolly adelgid might be able to glean some useful information from this study. Most of our findings are intuitive, and therefore validate the model scenario for further research, but do not give us a great deal of new insight. One insight that has come from this study is the significance of an initially infected hemlock's proximity to migration or other travel routes for a carrier species. Though mapping the paths of all potential carrier species through an area of forest would be an exceedingly difficult task, if the locations of certain "high traffic" areas, particularly for migratory species, are known, then the data suggest that these might be desirable locations for the introduction of control agents, especially those that would persist in the environment (such as natural predators).

Additionally, the preliminary data show, as previously stated, that in our scenario mobile control agents were more effective than stationary control agents at limiting the spread of HWA. This suggests that a highly mobile control agent, such as an entomopathogenic fungus, might be more effective in the natural environment than a more stationary natural predator or chemical control.

.

8. DESIGN CHALLENGES

8.1 A Non-Military Scenario

We were very excited to have the opportunity explore a new direction for Project Albert, but since this was a new direction there were some challenges involved in trying to model an environmental scenario in a distillation usually applied to military scenarios. These challenges, however, were relatively minor and not altogether unlike those faced by other modelers trying to apply the different features of particular distillations to their scenarios.

One feature not available in the Pythagoras distillation that may have proven useful in this scenario, as well as in future environmental studies, is a way for the agents to reproduce. Overall, however, we found Pythagoras to be fairly well suited to modeling this scenario, and would consider it for any future environmental studies.

8.2 Trend towards Complexity

One temptation in designing this scenario—a temptation that is common in most modeling—was to make the scenario progressively more and more complex. Because few systems are as intricate or complex in their components and interactions as an ecosystem, this was perhaps the most significant challenge in applying data farming techniques to model an environmental scenario. In the end, however, we felt that in these scenarios we had reached a good balance between detail and simplicity.

9. THE FUTURE

One of the most exciting plans for the future concerning this model is the possibility of incorporating GIS data into the terrain. In Pythagoras 1.7.4, terrain features must be drawn or programmed in by the modeler. Pythagoras 1.8, scheduled for release in September 2004, will allow the user to import files that can be turned into terrain backgrounds and features. We would like to use this ability to update the model scenario so that it can be compared to historical data on the spread of HWA in specific locations, or perhaps used to predict the future spread of HWA in certain areas and/or the effectiveness of different control method in those areas.

There is also the possibility, as previously mentioned, of studying the effect of cold temperatures on the spread of HWA, as well as designing a scenario that takes a different or more in-depth look at how entomopathogenic fungi might function as a control agent. It could also be interesting to research the remaining questions from our list, specifically concerning the effect of varying the amount of time HWA can persist on a carrier agent, as well as exploring how the geographic relationship between the location of initially infested trees and terrain features affects the spread of HWA.

Additionally, the possibility has been suggested of modifying/extrapolating some of the work performed on this project to studying, for the purpose of defending against such an attack, how a biological weapon agent might spread within an environment.

10. AN INTRODUCTION TO AGENT BASED MODELING, THE PYTHAGORAS ENVIRONMENT, AND DATA FARMING

Agent-based models are built "from the ground up," with agents or agent classes programmed with particular characteristics as well as various possible movement and engagement desires. In Pythagoras, agents can be endowed with a sidedness, indicated by their color along the red, green, and blue color bands. Through the use of "paintball" weapons this color can be changed, triggering the agents to change their behavior, for example a green "uninfected hemlock" agent firing a negative red color weapon changing to a yellow "infected hemlock" agent firing a positive red color weapon. Pythagoras also allows for the use of random variables as well as the assigning of tolerances around several of the values chosen for the agents – allowing for variation between agents of an identical agent class. This means that each random seed (set of initial conditions), as well as each random index (set of random conditions used throughout the progression of the scenario) will play out in a different manner with the possibility of a very different outcome.

Data Farming is a question-based type of computer modeling which uses simple models to approximate particular occurrences or series of events, either historical or hypothetical. It is designed to complement the more detailed traditional models generally in use today. Modelers use software programs ("environments") to design model scenarios that approximate the actual scenarios they are studying. These are designed specifically to address questions into which the modeler believes data farming might provide some insight. When a model scenario reaches a point in development where it is considered to acceptably approximate the reality being studied, the "data farmer" selects certain parameters that might be appropriate to vary across a range. The scenario is then generally sent to a supercomputer (in our case, a supercomputer at the Maui High Performance Computing Center in Hawaii) where it is run several times at each different combination of values for the parameters being data farmed across, providing data from several thousand, or more, individual runs. The data farmer then examines the data utilizing visualization tools to look for outliers and unexpected trends. He or she then often reassigns the range of certain parameters and resubmits the scenario to focus in on areas of particular interest in the data.

Based on their observations the data farmers can recommend specific areas of study for other modelers or field researchers with the goal of furthering our understanding of how and why certain events unfold the way they do.

We would like to extend special thanks to Bob Swanson and Ron Viloria at MHPCC, Dr. Gary Horne at MITRE, and Dr. Scott Costa at the University of Vermont.

11. REFERENCES

[1] Johnson, Hugh. The International Book of Trees. London: Mitchell Beazley Publishers Limited; New York: Simon and Schuster, Inc., 1973, p.88.

[2] Godman, R.M. and Kenneth Lancaster. "Tsuga canadiensis (L.) Carr. Eastern Hemlock." Silvics of North America. Vol. 1, Conifers. Tech. Coordinators Russel M. Burns and Barbara H. Honkala. Washington, D.C.: Forest Service, United States Department of Agriculture, 1990, p.609.

[3] Duncan, Wilbur H. and Marion B. Duncan. Trees of the Southern United States. Athens and London: The University of Georgia Press, 1988, p.38.

[4] Phillips, Roger. Trees of North America and Europe. Assist. Sheila Grant. Ed. Tom Wellsted. Line drawings by John White. New York: Random House, Inc.; London: Pan Books Ltd., 1978, p.209.

[5] Godman, Silvics, 611.

[6] State of New Hampshire Department of Agriculture, Markets and Food; Department of Resources and Economic Development. "Hemlock Woolly Adelgid Quarantine: Joint Quantine No. 1, Amendment No. 1, December 7, 2000," p.4. <http://www.nhdfl.org/protection_bureau/for_prot_images/hwa%20quarantine%202000.pdf>

[7] McClure, Mark S. "Role of Wind, Birds, Deer, and Humans in the Dispersal of Hemlock Woolly Adelgid (Homoptera: Adelgidae)." Environmental Entomology, 19(1) 36-43. 1990

[8] Hoover, Gregory A. "Hemlock Woolly Adelgid: *Adelges Tsugae* Annand." Entomological Notes, Penn State College of Agricultural Sciences – Cooperative Extension, Department of Entomology, 2000. <http://www.ento.psu.edu/extension/factsheets/hemlockwoolly.htm>

[9] Sanchez, Vicente. "Initial Estimates of the Number of Distinct Populations of Hemlock Woolly Adelgid in the Eastern United States Using Isoenzyme Profiles." In Proceedings: Hemlock Woolly Adelgid in the United States Symposium, held in East Brunswick New Jersey, 5-7 February 2002, ed. Brad Onken, Richard Reardon, and Jim Lashom. Rutgers University and USDA Forest Service, pp.354-357. < http://www.fs.fed.us/na/morgantown/fhp/hwa/pub/proceedings/initial_estimates.pdf>

[10] Lincoln, Frederick C., Steven R. Peterson, and John L. Zimmerman. Migration of Birds, U.S. Department of the Interior, U.S. Fish and Wildlife Service, Washington, D.C., 1998. An excellent resource on a wide variety of aspects of bird migration.

[11] Parker, Bruce L., Margaret Skinner, William Reid & Svetlana Gouli. "Entomopathogenic Fungi for HWA IPM – What's Next?" In Hemlock Woolly Adelgid Newsletter, Issue No. 5. USDA Forest Service, Northeastern Area State and Private Forestry Forest Health Protection, p.5. < http://www.fs.fed.us/na/morgantown/fhp/hwa/news5/hwa5.htm>

[12] Parker, Bruce L., Margaret Skinner, and Svetlana Gouli, and H.B. Teillon. "Cold Temperatures. Will They Limit Range Expansion?" In Proceedings: Hemlock Woolly Adelgid in the United States Symposium, held in East Brunswick New Jersey, 5-7 February 2002, ed. Brad Onken, Richard Reardon, and Jim Lashom. Rutgers University and USDA Forest Service, pp. 269-273 . <http://www.fs.fed.us/na/morgantown/fhp/hwa/pub/proceedings/cold_temp.pdf>

www.projectalbert.org