Climate Matching: Implications for the Biological Control of Hemlock Woolly Adelgid

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ABSTRACT

Classical biological control programs are faced with a daunting challenge: inserting a new species into an existing ecological system. In order for the newly introduced biological control species to survive and reproduce, the recipient ecosystem must provide the required biotic and abiotic requirements. The Adelgid Biological Control simulator (ABCs), a simulation program built to help evaluate the suitability of biological control species for the control of the hemlock woolly adelgid (*Adelges tsugae*), indicates that the Asian predatory beetle *Scymnus sinuanodulus*, imported to control the adelgid, can complete one generation annually, and that the production of a second generation is limited, not by the availability of warmth or prey, but by the need for adults to experience low temperatures to trigger oviposition. These findings support the use of a pre-conditioning regime in which adult beetles are first exposed to low temperatures prior to release to ensure oviposition begins in the year of release.

INTRODUCTION

Invasive species are a global environmental problem. The arrival, establishment, and spread of invasives bring both ecological and economic costs (Pimentel et al. 2000). Managing invasives often requires a multifaceted approach, including mechanical, chemical, and biological treatments. Efforts to control the hemlock woolly adelgid (*Adelges tsugae*) have included each of these with the pre-infestation removal of hemlock, the use of insecticides such as imidacloprid, and the release of non-native natural enemies for classical biological control. While pre-emptive salvage of hemlock eliminates the potential for infestation, it also eliminates this species from forested ecosystems. Insecticides can maintain hemlocks in a forested setting; however, the application of insecticides is costly and risks harming non-target organisms. Classical biological control may therefore play a key role in the maintenance of hemlock in eastern forests.

Although biological control is conceptually appealing, putting it into practice is a major challenge. Successful biological control programs are contingent on identifying natural enemies from the native range of the invasive, ensuring the biological control agent is host-specific, mass rearing the agent, and releasing it into an environment in which it can survive and reproduce. The population dynamics of the agent must then track that of the invasive species, reducing its numbers and/or its impact. In the case of *A. tsugae*, a number of predatory species of beetles have been identified, tested to examine their host range, mass reared, and released. However, establishment has been difficult to confirm, and questions regarding the potential for each species to survive and reproduce have been raised.

The interactions among a biological control agent, an invasive species, and the abiotic environment are complex, and although much is known about the biology of both *A. tsugae* and the biological controls identified and released, identifying key factors in the life history and the abiotic environment that may facilitate or prevent the establishment of predators is a major challenge. Simulation offers a tool to address these challenges by synthesizing information in a way that allows multiple factors to interact simultaneously. In this paper, we describe a new simulation linking the life history of *A. tsugae*, *Scymnus sinuanodulus*, and temperature.

The Adelgid Biological Control simulation (ABCs) was built using Stella™ (ISEE Systems™, Version 9.0). The structure of the simulation was based on the life histories of the adelgid and its predator, with each life history being broken into segments as organized in Figure 1. Imbedded within each segment are the rules that govern the behavior of the individuals within it, including: 1) the number of individuals entering that segment, 2) the percentage of individuals that survive that segment, 3) limiting factors that may arrest the development of individuals within that segment (for example, some life stages of *S. sinuanodulus* require adelgid eggs to complete development), 4) the time required to complete the segment, 5) the reproductive rate for individuals within that segment, if appropriate, and 6) the number of individuals leaving that segment. The code used to build the simulation is available from the author and provides the most up-to-date list of the rules used to define inter-variable interactions. This simulation was used to address three key questions regarding the suitability of *S. sinuanodulus* for release in the eastern United States:

1. Using exemplar southern and northern locations (Asheville, North Carolina, and Amherst, Massachusetts), do seasonal temperatures allow for *S. sinuanodulus* to complete development?
2. Does the timing of seasonal temperatures coincide with the availability of adelgid eggs, a requirement necessary for the completion of the *S. sinuanodulus* life-cycle?
3. Does the timing of temperature and adelgid egg availability allow for the completion of more than one generation of the beetle?

PARAMETER ESTIMATES

The parameters used in the simulation were based on information available in the published literature. Temperature values for Asheville, North Carolina, and Amherst, Massachusetts, were obtained through the online databases available at http://www.ncdc.noaa.gov (see Figure 2). Temperature requirements for the development of *S. sinuanodulus* were obtained from Lu and Montgomery (2001). The timing of the life-history of the adelgid was estimated using Figure 4 in McClure (1987).

SIMULATION RESULTS

The simulation suggests that seasonal temperatures in Asheville, North Carolina, allow the beetle *S. sinuanodulus* to complete development; however, the beetle produces only one generation per year. Closer examination of the simulation results indicate that the lack of a

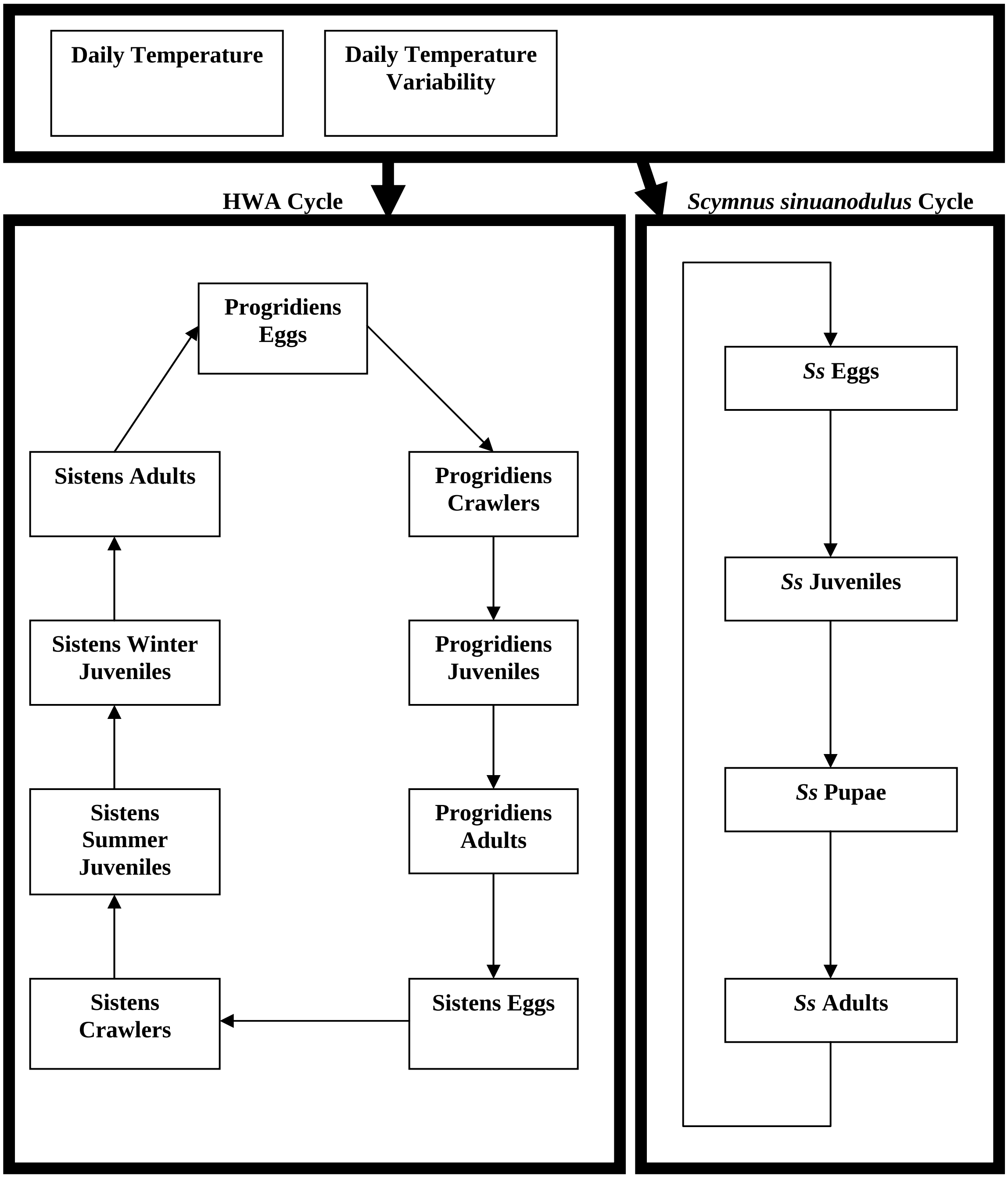

Figure 1. Adelgid Biological Control simulation structure.

second generation is the result of inadequate low, rather than high temperatures. As Lu and Montgomery (2001) discuss, *S. sinuanodulus* requires exposure to temperatures below 5°C to initiate oviposition. As Figure 3 shows, beetles were "released" in the simulation in the spring of the second year but did not produce eggs until the following spring. The lag between release and oviposition highlights the importance of pre-treating the beetles prior to releasing them (Montgomery, pers. comm.).

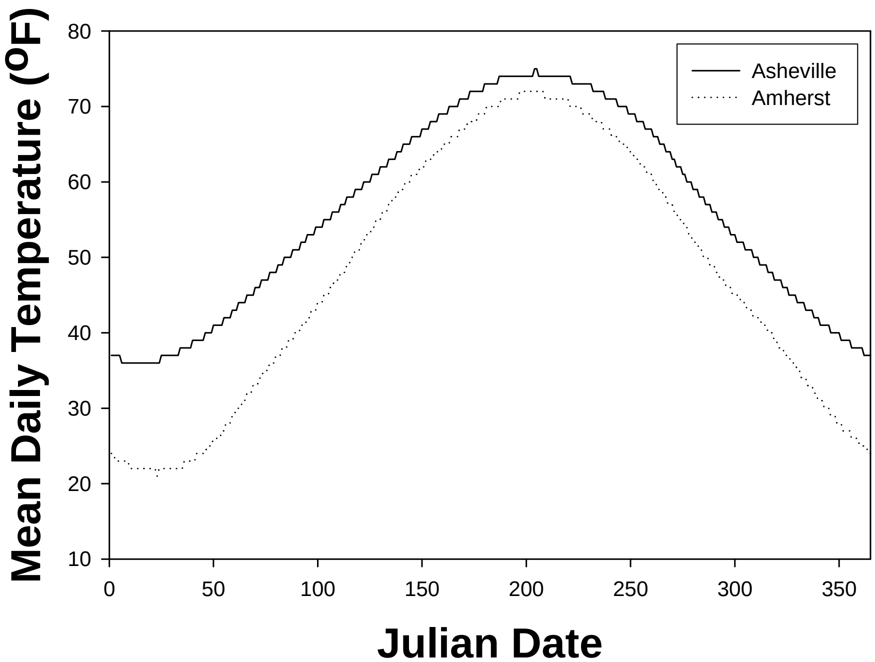

Figure 2. Temperature profiles for Asheville, NC, and Amherst, MA.

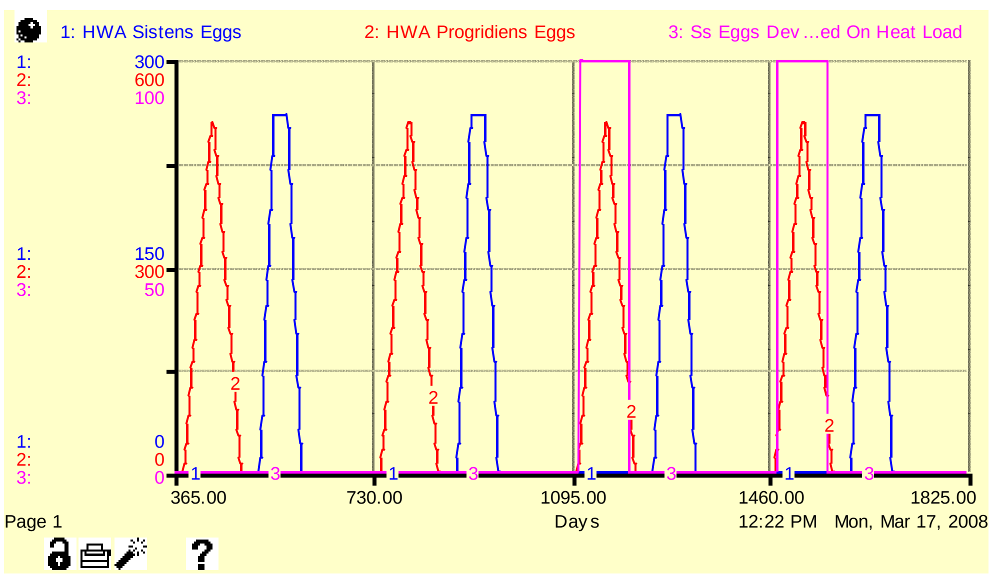

Figure 3. Simulation results for Asheville, NC.

Using temperatures from the northern site (Amherst, Massachusetts), the simulation yields similar results (Figure 4). Again, the production of a second generation is limited, not by available heat, but by the need for adult beetles to be exposed to low temperatures before they will initiate oviposition. However, the simulation does show that the overall lower temperatures in the north results in an lengthening of the time it takes for the beetle to complete each of its life stages.

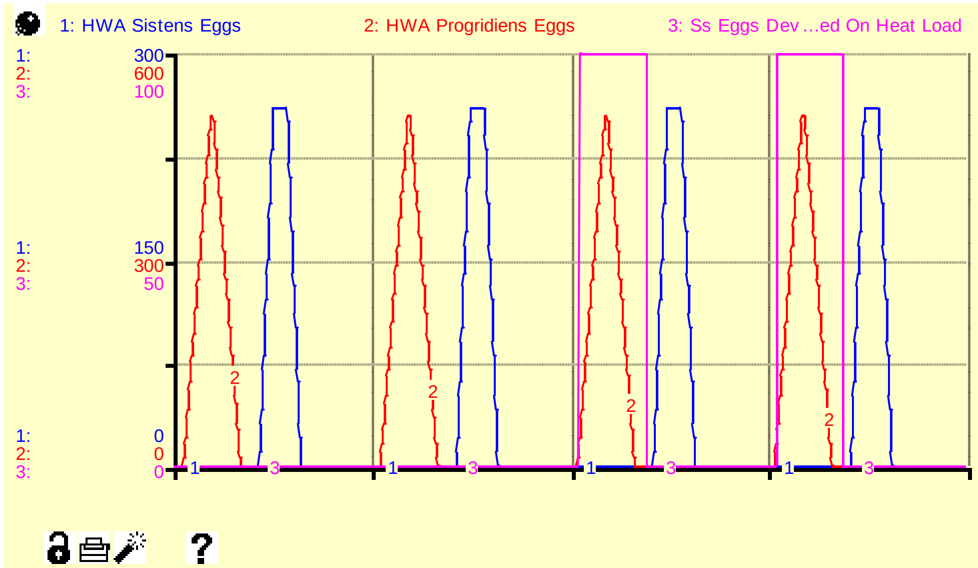

Figure 4. Simulation results for Amherst, MA.

SUMMARY

These two simulations suggest three patterns in the population dynamics of the predatory beetle *Scymnus sinuanodulus*. First, the simulations from both the northern and southern locations indicate that seasonal warmth is not likely to be a limiting factor in the completion of the beetle's life-cycle. To the contrary, the need for adults to experience low temperatures to initiate oviposition is a limiting factor, as the spring release of the beetles in the simulation shows that eggs were not produced until the following spring. In management applications, beetles released in the spring should be first exposed to low temperatures if eggs are to be laid in the current year. Failure to pre-condition *S. sinuanodulus* adults before field release may result in a delay in the appearance of the F_1 generation. Compounding the problem, not all adults may survive the year between release and oviposition, which may reduce establishment success.

The second pattern shown by both simulations is that *S. sinuanodulus* will likely lay its eggs in synchrony with *A. tsugae* sistens. As the beetle eggs hatch and the juveniles begin to feed, they may be able to impact the eggs laid by both sistens and progridiens. The potential for this impact further highlights the importance of pre-conditioning beetles before release to encourage oviposition in the first spring.

Finally, these simulations specifically (and the Adelgid Biological Control simulation environment more generally) highlight the need for additional information on the biology and ecology of the hemlock woolly adelgid and its natural enemies. For example, these simulations assume that the beetles survive for one year and so have one reproductive event. Yet, laboratory studies (Montgomery, pers. comm.) have shown that the beetles can survive two years and perhaps even longer, potentially producing more than one generation of eggs. This generational overlap may result in increased population growth rates and cause the population dynamics of the beetle to behave like that of a bivoltine species. The simulation also highlights the need for a better understanding of the environmental mechanisms that drive the development of the hemlock woolly adelgid. The timing of the availability of eggs is likely to change from one year to the next as winter and spring conditions vary. These changes in timing may have an impact on the beetles that depend on the adelgid populations; yet, little is known about how the timing of adelgid development varies or how this may impact natural enemies. As research on these species continues and as additional information on the biology and ecology of the hemlock woolly adelgid and its natural enemies becomes available, it can be integrated into the simulation to improve our understanding of this complex system, and to explore new management options.

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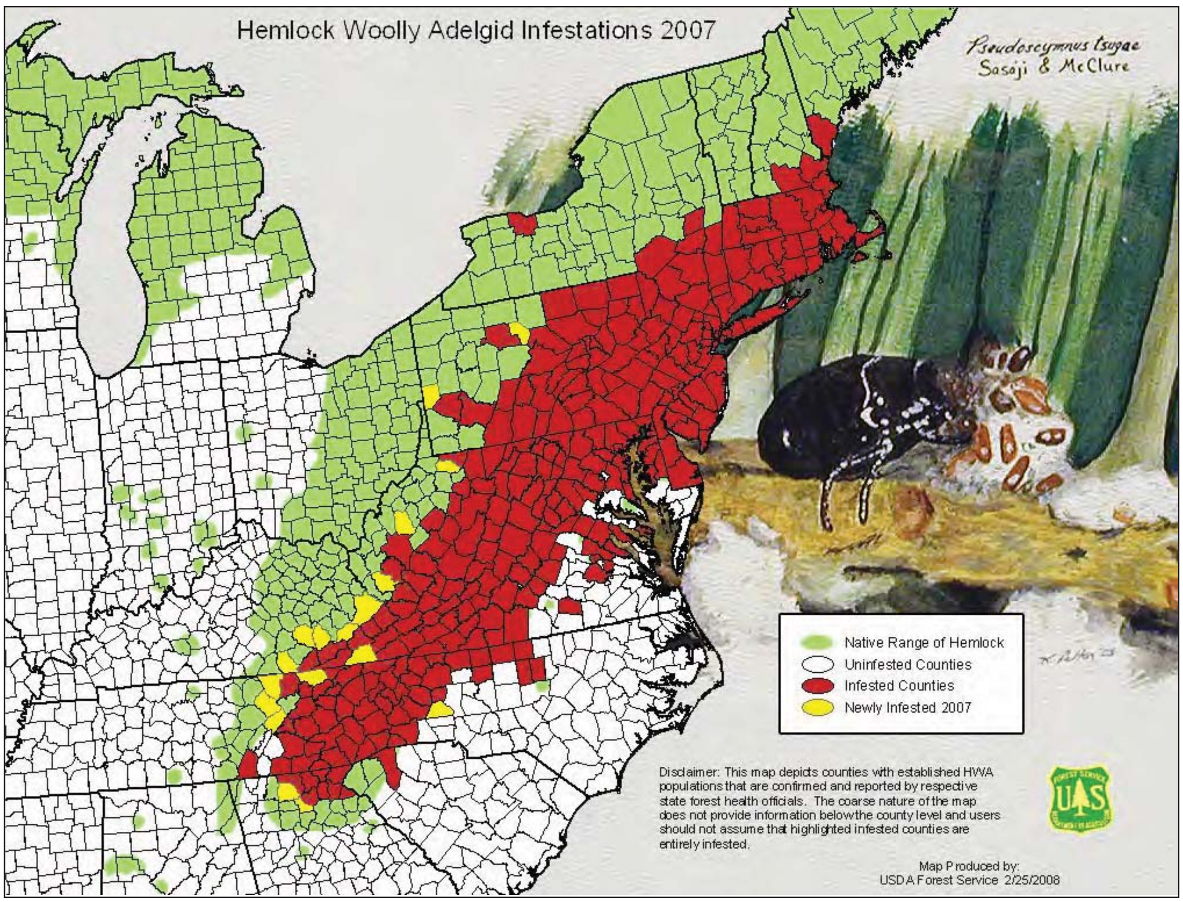

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