Computer simulation model for biological control of maize weevil by the parasitoid *Anisopteromalus calandrae*[1]

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Abstract

An age-structured computer simulation model was developed to help evaluate different strategies for biological control of the maize weevil, *Sitophilus zeamais*, in stored maize by the parasitic wasp, *Anisopteromalus calandrae*. Parameters of the model were based on detailed laboratory life history and functional response studies conducted at 25°C. Because of the long adult lifespan and oviposition period of the maize weevil, the parasitoid can only slow the growth of, rather than reduce, the pest population during typical storage periods. Establishment of a sufficiently large parasitoid population during the first host generation is critical to the success of biological control in this system. Simulation was used to explore the efficacy of various release strategies including time of first parasitoid release, numbers per release, time between consecutive releases, and number of consecutive releases. An optimal strategy includes two or three releases, of about ten times as many parasitoids as adult weevils at 9-day intervals as soon as the first hosts of suitable size (> 15 days old) are available.

Introduction

Anisopteromalus calandrae (Howard) (Hymenoptera: Pteromalidae) is a cosmopolitan parasite of *Sitophilus* weevil larvae, that develop inside kernels of stored maize. Its prevalence in the field and ease of rearing in the laboratory suggest it has potential for augmentative biological control of maize weevils, *Sitophilus zeamais* Motschulsky (e.g. Ghani and Sweetman 1955; Williams and Floyd 1971; Arbogast and Mullen 1990; Smith 1992, 1993a,b; Smith and Press 1992; Wen et al. 1994). Because of the disruptive, seasonal nature of grain storage and the widespread occurrence of *A. calandrae*, it is thought that successful use of this parasitoid will depend on inoculative or augmentative releases (Parrella et al. 1992). Such a strategy would involve obtaining parasitoids from an insectary and releasing them into storage containers at the beginning of the storage cycle. Determining how many and how frequently to release is critical to developing a cost-effective pest control strategy. Yet, such information is difficult (or expensive) to obtain from experimentation because the uncertainty of the effect of spatial scale on insect behaviour would require large-scale field experiments. However, it is possible that some of these questions can be answered, at least partially, by using computer models to simulate the host-parasitoid population dynamics. Such models permit us to quickly see the effects of changing certain parameters, such as number of parasitoids released or frequency of releases.

The purpose of this study is to develop a simple deterministic computer model to simulate host-parasitoid population dynamics. Such a model can be used to evaluate the potential effectiveness of *A. calandrae* and to help design efficient strategies for implementing augmentative biological control programs.

Materials and Methods

The model is based on data from laboratory experiments at 25°C measuring age-specific fecundity, adult survivorship, and development time of both species (Birch 1953; Hwang et al. 1983; Smith 1992; Throne 1994). Progeny sex ratio, host size preference, and functional response of the parasitoid was also measured (Smith 1993b, 1994).

The program was written using STELLA® software (High Performance Systems, Inc., Lyme, NH) on a Macintosh®SE/30 computer (Apple Computer, Cupertino, CA). This software provides a graphically-oriented user-friendly interface for constructing diagrams representing the model structure (see Bogen 1989 for a review). Relationships between different compartments of the model can be represented by an equation, conversion table, or by drawing a graph, depending on what type of data are available. The model is automatically converted to a set of differential equations which are solved numerically. Computation algorithms, such as Euler's or Runge-Kutta method, and the time step are selected by the user. The output is graphical, tabular, or presented as animated diagrams, and one can easily choose which variables to view.

This simulation model incorporates age structure, distributed-delay development time (which represents variation in development time), host size (age) preference, and functional response. Thus, adult parasitoids of different ages have different mean daily fecundity and different mortality rates (Fig. 1). At each daily time step the insects progress from one age class to the next, with an appropriate loss from mortality. Variation in development time was represented by fixed proportions of immatures skipping one or more age classes early in development to achieve the expected frequency distribution for adult emergence of females (Fig. 1). The model had a time step of 1 day, with individual insects moving from one age class to the next each day (Fig. 2). Mortality was applied to each adult age class based on the observed survivorship curves (Birch 1953; Smith 1992). Immature mortality of weevils, due to causes other than parasitoids, was divided evenly between those too young to be parasitised and those too old, so that half of this mortality would reduce the number of suitable hosts available.

The functional response (the relationship between parasitism rate and the relative abundance of host and parasitoid populations [Holling 1959]) fit a typical type II curve (Smith 1994). Only host larvae larger than 1.0 mm in diameter (≥16 days old at 25°C) are parasitised by *A. calandrae* (Smith 1993b). The functional response was modelled by scaling the curve (Smith 1994) so that relative parasitism (scale 0 to 1)

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[1] This paper reports the results of research only. Mention of a proprietary product does not constitute an endorsement by the USDA.

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was a function of the ratio of the number of suitable hosts to the number of parasitoid eggs available. The number of eggs available is a function of age-specific fecundity (i.e. maximum oviposition rate) and number of parasitoid females in each age class (Fig. 2). Separate life cycles for *A. calandrae* and *S. zeamais* were connected by parasitism with each attack corresponding to the death of a weevil larva and the oviposition of a parasitoid egg (Fig. 3).

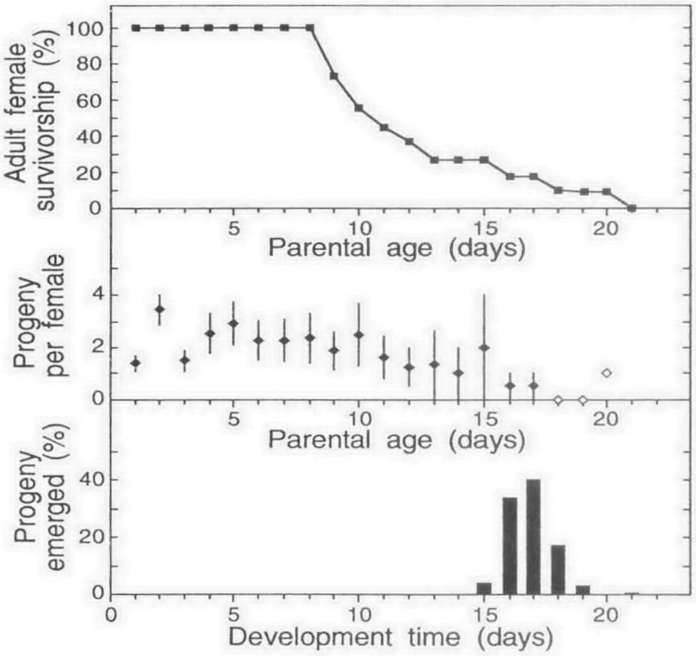

Fig. 1. Demographic data of *A. calandrae* used in the population model, adult female survivorship, age-specific fecundity (x± SE;◇ , indicates progeny of single female), female development time (Smith 1992).

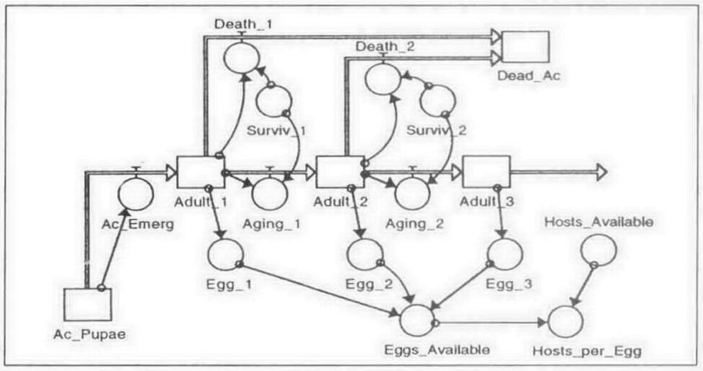

Fig. 2. Diagram of part of the computer model representing the adult parasitoids. □, variables containing the number of parasitoids for each age class; ○, functions that control the flow of individuals from one stage to the next; O, variables used in calculations.

Results and Discussion

This simple model can be used to explore several aspects of the population dynamics of this system. First, it is evident that the long adult lifespan and prolonged oviposition period of *S. zeamais* prevents the parasitoid from reducing weevil populations during the first several generations (Fig. 4). However, the parasitoid can still be useful because it is able to reduce the rate of population growth of the weevil. Although this model is too simple to be used to predict the outcome of parasitoid releases in field situations, it does enable us to start exploring some important questions such as how many, how often, and when to release.

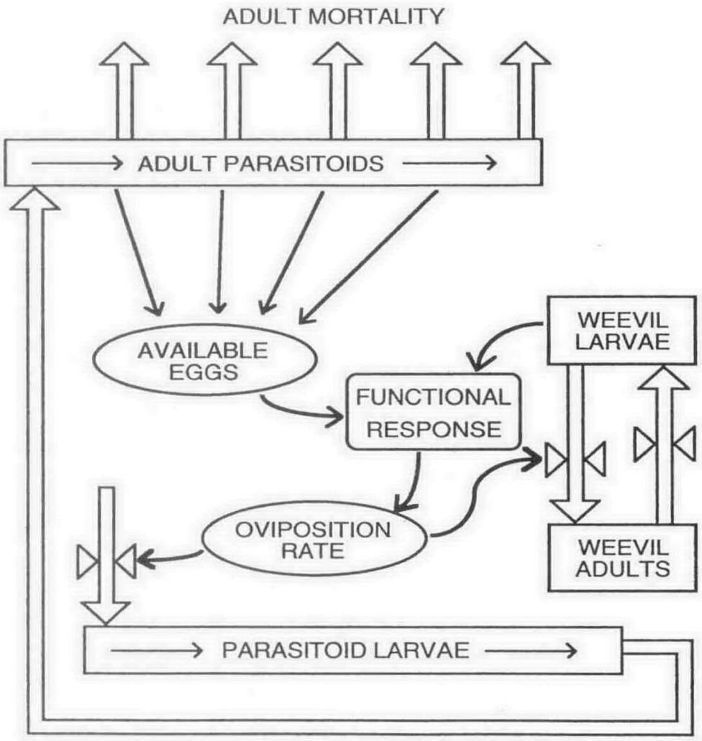

Fig. 3. Schematic diagram of the computer model; see text for explanation.

Delay until first release

Determining when to start releases depends on the age structure of the target weevil population. If the grain is being invaded by adults but no immatures are present (as after fumigation), then there is a delay of about 16 days (at 25°C) until the first progeny would be large enough to be parasitised (Fig. 4, top). However, if the grain is already infested when it enters storage, then suitable hosts may already be present. In this case, the first parasitoid releases should be as soon as possible to minimise the number of weevils maturing past the vulnerable age class.

Size of release

The effect of releasing different numbers of *A. calandrae* in a single release on day 15 to control progeny of 100 newly emerged *S. zeamais* (1:1 sex ratio) released on day 0 was simulated (Fig. 4). Releasing more parasitoids caused greater reduction of weevils, but the efficiency per parasitoid decreased rapidly. Releasing ten *A. calandrae* reduced the weevil population by 71% (from 133550 to 38 174 on day 120), 100 parasitoids reduced the weevils 94%, and 1000 parasitoids reduced them 97%. Releasing more parasitoids caused no significant further reduction of the weevil population. This suggests no need to release more than 10 times as many parasitoids as adult weevils, and that a 1:1 ratio is actually very efficient (assuming that there is not already a large number of immature weevils).

Interval between consecutive releases

It should be noted that there is a substantial gap between the first and second parasitoid generations (Fig. 4). This permits a cohort of weevil larvae to escape parasitism, which results in a

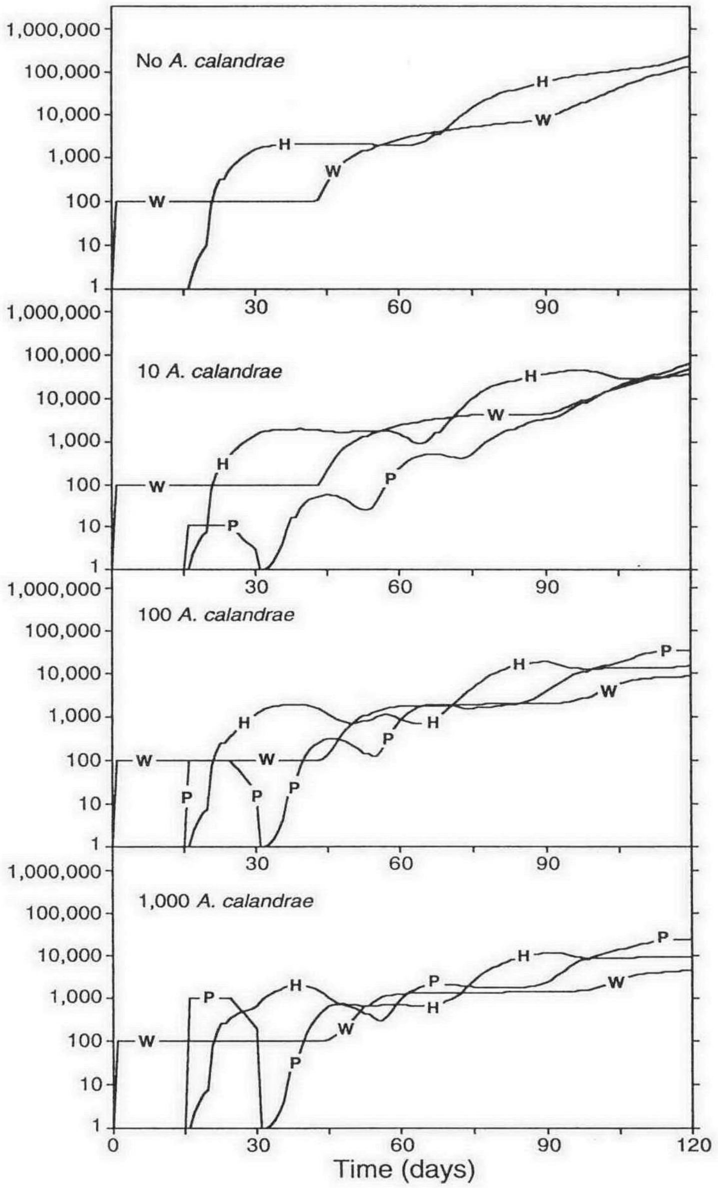

Fig. 4. Effect of releasing different numbers of adult *A. calandrae* on day 15 to control progeny of 100 adult *S. zeamais* released on day 0; H, suitable hosts (weevil larvae > 1.0 mm diameter); P, adult parasitoids; W, adult weevils.

subsequent pulse of adult weevils about 2 weeks later. It is important to minimise the occurrence of such gaps in parasitism, because each gap causes a ratcheting increase in the pest population.

Determining the optimal time interval between consecutive parasitoid releases can be easily obtained by simulation. In this simulation 2 pairs of adult weevils were released on day 0 and one pair of parasitoids was released on day 15 and again 9 to 12 days later (Fig. 5). In the 12 day interval simulation, note the substantial reduction in the adult parasitoid population (P) for several days between the first and second cohorts (on days 25–28). This corresponds to a sharp peak in the hosts-per-egg ratio (E), which indicates that there are many more hosts available than can be parasitised. As the interval between the two parasitoid releases is reduced the depression in the adult parasitoid population disappears and the peak in the hosts-per-egg ratio shrinks. These simulations indicate that the interval between consecutive releases should be no greater than 9 days at 25°C. The secondary peak in the hosts-per-egg ratio (at day 33) indicates that a third parasitoid release may be useful.

Number of consecutive releases

The effect of making different numbers of weekly parasitoid releases was simulated using the same parameters as in the preceding section. One release reduced the adult weevil population by 95.3% on day 120 (Fig. 6). Two and three releases reduced the weevils by 97.8% and 98.7 %, respectively, relative to no parasitoids. Additional releases achieved no further reduction of the weevils, even when releases continued weekly. This is because the number being released (1 pair) was so small relative to the number of emerging parasitoid progeny (Fig. 5).

Future development

This simulation model needs to be expanded to include the effects of temperature, the principal abiotic variable affecting population dynamics in the stored-grain environment. This will require quantitative life history data for both the pests and parasitoids over the range appropriate to field conditions. In temperate regions it is particularly important to know what happens to the host and parasitoid populations during the winter because the survivors of these populations play a major role in the spring when the grain warms. Can inoculative releases at the start of storage in the fall be relied on to ensure continued control in the spring? It is also important to learn more about the efficiency of parasitoids at low host densities, representative of those in commercial storage. The role of interference among parasitoids can also be added (Wen et al. 1994). The fact that strains of this parasitoid are resistant to malathion (Baker and Weaver 1993) also indicates that it can be used to complement residual insecticides, so modelling could incorporate the application of insecticides and their degradation (Arthur et al. 1991). Such information should eventually improve computer models to the point where they can be incorporated into expert systems for integrated pest management of stored grains (Compton et al. 1992; Flinn and Hagstrum 1990).

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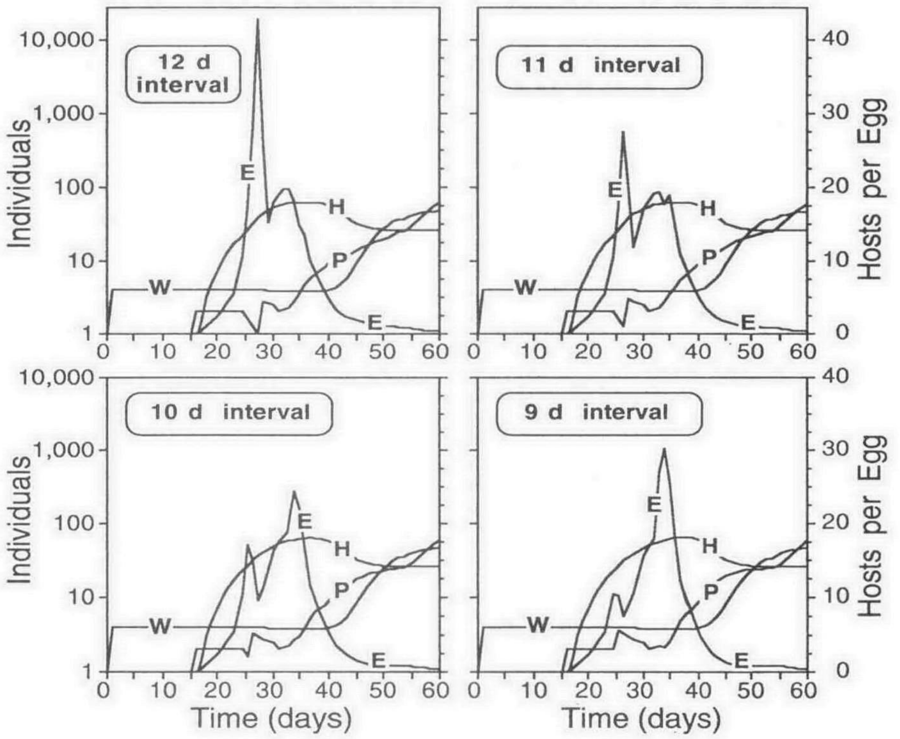

Fig. 5. Effect of changing the release interval of *A. calandrae* (2 pairs, starting on day 15) to control progeny of 4 pairs adult *S. zeamais* released on day 0; E, ratio of suitable hosts to available parasitoid eggs; H, suitable hosts (weevil larvae > 1.0 mm diameter); P, adult parasitoids; W, adult weevils.

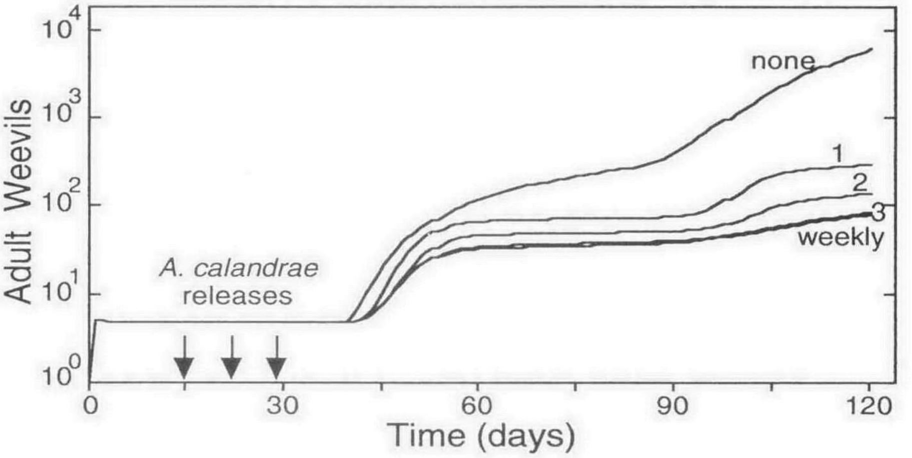

Fig. 6. Effect of the number of sequential releases of *A. calandrae* (2 pairs at 7 day intervals, starting on day 15) to control progeny of 4 pairs adult *S. zeamais* released on day 0.

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