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Mating rates between sterile and wild codling moths (*Cydia pomonella*) in springtime: A simulation study

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ABSTRACT

The sterile insect technique (SIT) can be a powerful method for pest control without the negative environmental effects of conventional pesticides. The goal is to induce pest population collapse by arranging conditions where wild females mate only with sterile males and thus do not produce offspring. In applying the SIT, it can be important to understand both how subtle alterations of sterile and wild insect behaviour alter the effectiveness of the SIT in different applications, and how this is reflected in the data gathered through associated monitoring devices, often pheromone traps.

Our work in this paper is motivated by the use of SIT against orchard pests, particularly the codling moth (*Cydia pomonella*). We investigate how individual behaviours affect the mating rate between wild females and sterile males, and the corresponding sterile to wild trap catch ratio, through a preliminary individual-based model. Our analysis suggests that the sterile males may not be effective at interfering with mating between wild moths during springtime releases, while at the same time monitoring information gathered from trap catches may give no indication of reduced effectiveness of the SIT.

1. Introduction

The sterile insect technique (SIT, also known as the sterile male technique), developed by Knipling (1955), has made it possible for troublesome agricultural pests to be completely eliminated from impressively large areas (Klassen and Curtis, 2005). The most notable of these is the New World Screwworm, which caused billions of dollars of damage annually in the southern United States. Through an intensive and cooperative program between the United States, Mexico and Central American Countries, the New World screwworm was exterminated north of Panama, and a barrier against reinvasion held there (Klassen and Curtis, 2005). The SIT has been used against a wide variety of insect pests, including Tephritid fruit flies, onion maggot, tsetse flies, mosquitoes, Coleoptera and Lepidoptera. A summary of these efforts is presented in (Klassen and Curtis, 2005). Past successes indicate that the SIT, especially when used as part of an appropriate area-wide integrated pest management program, has significant potential to enable control of agricultural pests below economic levels and at a lower cost to the environment than current conventional methods (Klassen and Curtis, 2005).

Mathematical models of the SIT have been used since the method was first proposed by Knipling. A review is provided in Barclay (2005). These models determine the overflooding ratio (sterile:wild numbers) necessary for the SIT to be effective under different assumptions. Of relevance to this paper are the models that investigate how the overflooding ratio is affected when females engage in re-mating behaviour, when sterile males have reduced competitive ability, and when the wild population has a clumped rather than uniform distribution. In each case, the models show that the SIT can still be effective, but the overflooding ratio required for control of the pest is increased.

These results were obtained with models that were largely either nonspatial or included space implicitly, though a few spatially explicit models have been studied (Barclay, 1992; Lewis and van den Driessche, 1993; Manoranjan and van den Driessche, 1986). Existing models also operate on a multi-generational time scale and so the predicted overflooding ratios are based on steady state results which are only strictly valid for very long time periods (multiple generations). In this paper, we develop a spatially explicit individual-based model (IBM) over a much smaller time scale, that is, less than a season. Thus, we are investigating the transient behaviour of the sterile–wild insect system. We also include pheromone traps and trap catch data in our output, so that we can compare actual mating rates between sterile males and wild females with sterile male to wild male trap catch ratios.

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Our work is motivated by the case of the codling moth (*Cydia pomonella*), a pest that, in its larval stage, damages and significantly reduces the marketability of pome fruits. Controlling the codling moth population is a major goal of agricultural research. In the Okanagan and Similkameen Valleys of southern British Columbia (BC), Canada, a sterile insect release (SIR) program based on the SIT has operated since 1994 (Bloem et al., 2005). There are only two sterile moth projects worldwide, and only one on the codling moth. Hence, there is a dearth of practical experience or theory available, and the program relies on data from fly biology, which is very different.

By 2001, the SIR program in BC had succeeded in reducing the wild population to very low levels. Theoretically, however, it should only have taken three years to reach this point, and by 2004 there were signs that the wild moth population was increasing (Thistlewood et al., 2004). A possible explanation for this result, is that the assumptions underpinning the SIT theory may be violated in the springtime when temperatures are cooler and there is more rain. In southern BC, codling moth has two full generations (one in spring and one in summer) and a partial third generation (in the fall) annually. There are two moth behaviours which appear to be critically affected in springtime populations: sterile male competitiveness and wild moth population clumping. In addition, little is known about the propensity for and effect of movement by calling females, and there is evidence that wild females may exhibit selectivity in mate choice through re-mating, thus increasing their odds of finding a wild male.

Previous IBM models of moth movement (Barbosa et al., 2005; Pearson et al., 2004; Yamanaka et al., 2003) concentrated on moth behaviour in a relatively small area and short period of time. The present study is more ambitious in scale, as we are interested in the dispersal behaviour of the wild and sterile codling moths, both male and female, over a period of one week and over a domain the size of an orchard. In particular, we wish to investigate how moth behaviour affects two key quantities: the proportion of wild females that mate with sterile moths, and the total number of sterile vs wild moths caught in pheromone traps. The moth behaviours we consider are: reduced male competitiveness, wild moth population clumping, propensity to movement by calling females and selectivity in mate choice by wild females.

In Section 2 we outline the experimental field research on which our model is based. In Section 3 we present the model and in Section 4 we describe the simulation experiments we performed and associated results. Conclusions and future extensions of the model are outlined in Section 5.

2. Experimental program and questions

The SIR program is based out of a facility in Osoyoos, BC, where codling moths are mass-reared, marked and sterilized with γ-radiation. The irradiated moths are released in large numbers throughout the Okanagan–Similkameen Valleys at bi-weekly intervals using a blower mounted on an ATV driving in designated rows of every orchard. Host trees in adjacent noncommercial sites are removed or populations maintained at very low levels. The success of the program is evaluated at harvest from the proportion of damaged fruit, and also throughout the growing season by means of pheromone traps placed in pome fruit trees throughout the region. Theoretically, if the ratio of sterile male moths to wild male moths in every trap is no less than 40:1, the sterile population is sufficiently large so as to overwhelm the wild population and drive it to extinction. Further details about the SIR program can be found in Thistlewood et al. (2004) and references therein.

The experience of the SIR program in the Okanagan–Similkameen Valleys has raised a number of questions about SIT as applied to *C. pomonella*. In this paper we present a preliminary study of four specific issues, all in the context of springtime releases of sterile moths:

1. The response of male mass-reared moths to pheromone stimuli in spring may differ significantly from that of wild moths. Sterile male moths appear to initiate flight and mate-finding at a different time of day than wild moths and their success in mating is greatly reduced (Judd et al., 2006). This is perhaps caused by a difference in the moths' response to environmental stimuli.
2. The theory behind the original SIR program protocol and effectiveness measures assumed that the spatial structure of the moth population could be ignored. This is probably true at high population densities. The application of the SIT; however, results in a significant decrease in the wild population, which means that either for maintenance of low population densities or for eradication of the moth, low density dynamics are important to the SIR program. At these low populations, the distribution of moths, especially with respect to overwintering and emergence sites, is highly clumped (Duthie et al., 2003). Past modelling efforts show that aggregation of the pest population decreases the efficiency of control by the SIT (Barclay, 1992; Barclay and Judd, 1995).
3. Little is known about the dispersal behaviour of wild or sterile female moths in the field. It has been suggested that female movement can have a strong effect on mating success (Knight, 2007; Pearson et al., 2004).
4. It has been observed that wild females are occasionally unsatisfied with the spermatophore delivered by a sterile male, and so will continue calling for a mate even after mating (Knight, 2007). The fraction of females who engage in this behaviour is small, but they can have an important effect on the success of the SIT in a nonspatial context (Barclay, 1984; Vreysen et al., 2006).

To investigate these issues, we construct an IBM for moths in a traditional pome fruit orchard (an orchard with tall, spreading fruit trees planted at regular intervals in regularly spaced rows). Our simulation models moth dispersal, mating, death and capture in pheromone traps. To calibrate our IBM we use data from dispersal experiments carried out by Drs. Thistlewood and Judd in a traditional apple orchard at the south end of an experimental site in the Similkameen Valley (Thistlewood and Judd, 2003b). A square grid of pheromone traps, placed at a distance of 1 per hectare, were hung in the orchard. Eight thousand marked sterile moths, occurring at a roughly 1:1 ratio males:females, were released at the centre of the orchard and the traps were monitored weekly for the lifespan of the moths. The dispersal of the moths was inferred from their recapture counts in the traps. The trapping grid was established in 2003, and three releases were performed within the grid that spring and the following spring.

3. The model

The goal of our modelling effort is to discover how variations in real moth behaviour may affect the wild–wild mating rate and the sterile–wild trap catch ratio in the field. Our approach is to develop a model that is a reasonable, rather than accurate, imitation of the real moth-trap orchard system, and that allows us to investigate our theoretical questions. Given this model, which we outline in this section, we obtain baseline data (see Section 4.1), and then observe how these data are