Supporting Information

Miller et al. 10.1073/pnas.0908453107

Section A: Derivation of Trapping Equation

It follows from Fig. 1 that mean capture per male ($C\,/_{\text{♂}}$) can be estimated as the product of the probabilities for steps 1–5 averaged across males. The probable cumulative catch per trap (C) operating in the absence of competing attractant sources would be $pC\,/_{\text{♂}}$ multiplied by the density of responsive males (♂_{den}) within the range of that trap over time. Knipling (1) reasoned similarly, but made no allowance for inefficiencies in trap findability (Fig. 1, steps 1–4) or trap efficiency in ensnaring males. With these provisions, the overall equation predicting capture by a given trap (T) then becomes:

$$C = T\text{ findability} \times T\text{ efficiency} \times T\text{ retention time} \times \text{♂}_{\mathrm{den}}. \qquad \textbf{[S1]}$$

Findability is an interaction of responsive males with the plume from the pheromone point source. It rises with plume size and both plume and male mobility (vagility). Because retention time for an ensnared moth is lifelong (1.0), this parameter is silent for traps and is sometimes ignored in following equations.

Section B: Derivation of a Realistic Competitive-Attraction Equation

Building on Knipling (1) and Miller et al. (2, 3), we reasoned that catch per trap (C) present with various densities of competing females (♀) and pheromone dispensers (D) acting as attractive point sources would conform to Eq. **S2** under the simplified case where $T_{\mathrm{den}} = 1$ and the findability and retentiveness of T = ♀ = D = 1.0. Catch per trap then becomes (1 trap / total density of attractive sources) × ♂_{den} =

$$C = \text{♂den}/(1 + \text{♀}_{\mathrm{den}} + D_{\mathrm{den}}). \qquad \textbf{[S2]}$$

However, Expt. 1 established that source findabilities < 1.0 must be accommodated. Moreover, when an attractive source does not ensnare the male, retention will be less than lifelong (<1.0). We offer the more mature Eq. **S3** as an experimentally testable explanatory model for competitive attraction. Underlying assumptions are

$$\begin{aligned} C = {} & T\text{ findability} \times T\text{ efficiency} \times \text{♂}_{\mathrm{den}}/[1 \\ & + (\text{♀findability} \times \text{♀retentiveness} \times \text{♀}_{\mathrm{den}}) \\ & + (D\text{ findability} \times D\text{ retentiveness} \times D_{\mathrm{den}})], \qquad \textbf{[S3]} \end{aligned}$$

that males and females become randomly distributed through space, dispensers are uniformly distributed, and males interact through time with attractant sources according to rules of probability applied to random draws of similar articles from a common pool, e.g., a given card from a deck of cards. D retentiveness can be interchanged with disruption time (D time).

Section C: Derivation of Eqs. S4 and S5

1. Equation for Calculating D_a. When T equals trap, $T_{\mathrm{den}} = 1$, T retention time = 1 reproductive lifespan, $\text{♀}_{\mathrm{den}} = 0$, D equals dispenser, D time equals disruption time equals dispenser retentiveness, then catch per trap (C) = T findability × T efficiency × ♂_{den} / [1 + (D findability × D time × D_{den})] as per Eq. **S4**. Eq. **S5**, D_a = D findability × D time / (T findability × T efficiency) = $1/D_{\mathrm{den}}$ [(♂_{den} / C) – 1/(T findability × T efficiency)] was derived by solving Eq. **S4** for D findability × D time and then substituting this expression for D findability × D time in D_a = D findability × D time / (T findability × trap efficiency) and then simplifying as follows:

$$C = \frac{T\text{ findability} \times T\text{ efficiency} \times \text{♂}_{\mathrm{den}}}{1 + (D\text{ findability} \times D\text{ time} \times D_{\mathrm{den}}).} \qquad \textbf{[S4]}$$

$$\begin{aligned}
& C + C(D\text{ findability} \times D\text{ time} \times D_{\mathrm{den}}) \\
& \quad = T\text{ findability } \times T\text{ efficiency} \times \text{♂}_{\mathrm{den}} \\
& C \times D\text{ findability} \times D\text{ time} \times D_{\mathrm{den}} \\
& \quad = (T\text{ findability} \times T\text{ efficiency} \times \text{♂}_{\mathrm{den}}) - C \\
& D\text{ findability} \times D\text{ time} \times D_{\mathrm{den}} \\
& \quad = \frac{T\text{ findability} \times T\text{ efficiency} \times \text{♂}_{\mathrm{den}}}{C} - \frac{C}{C} \\
& \quad = \frac{T\text{ findability} \times T\text{ efficiency} \times \text{♂}_{\mathrm{den}}}{C} - 1 \\
& D\text{ findability} \times D\text{ time} \\
& \quad = \frac{T\text{ findability} \times T\text{ efficiency} \times \text{♂}_{\mathrm{den}}}{D_{\mathrm{den}} \times C} - \frac{1}{D_{\mathrm{den}}} \\
& \text{Substitute} \frac{T\text{ findability} \times T\text{ efficiency} \times \text{♂}_{\mathrm{den}}}{D_{\mathrm{den}} \times \mathrm{C}} - \frac{1}{D_{\mathrm{den}}} \\
& \quad \text{for D findability} \times D\text{ time in } D_a = \frac{D\text{ findability} \times D\text{ time}}{T\text{ findability } \times T\text{ efficiency}}
\end{aligned}$$

$$\begin{aligned}
D_a & = \frac{\dfrac{T\text{ findability} \times T\text{ efficiency } \times \text{♂}_{\mathrm{den}}}{D_{\mathrm{den}} \times C} - \dfrac{1}{D_{\mathrm{den}}}}{T\text{ findability} \times T\text{ efficiency}} \\
& = \frac{T\text{ findability} \times T\text{efficiency} \times \text{♂}_{\mathrm{den}}}{T\text{ findability} \times T\text{efficiency} \times D_{\mathrm{den}} \times C} \\
& \quad - \frac{1}{T\text{ findability} \times T\text{ efficiency} \times D_{\mathrm{den}}} \\
& = \frac{\text{♂}_{\mathrm{den}}}{D_{\mathrm{den}} \times C} - \frac{1}{T\text{ findability} \times T\text{ efficiency} \times D_{\mathrm{den}}} = D_a \\
& = \frac{1}{D_{\mathrm{den}}}\left[\left(\frac{\text{♂}_{\mathrm{den}}}{C}\right) - \left(\frac{1}{T\text{ findability} \times T\text{ efficiency}}\right)\right]. \qquad \textbf{[S5]}
\end{aligned}$$

2. Equation for Calculating Disruption Time. Disruption time, including its after-effects, can be directly calculated using Eq. **S6**, derived from rearranging Eq. **S4**.

$$\begin{aligned} \text{Disruption time} = {} & (1/D\text{ findability} \times D_{\mathrm{den}})(T\text{ findability} \\ & \times T\text{ efficiency} \times \text{♂}_{\mathrm{den}}/C) - 1. \qquad \textbf{[S6]} \end{aligned}$$

Section D: Quantification of Male Catch in Monitoring Traps Due to Presence of Virgin Females

Inhibition of male captures in monitoring traps per virgin female deployed in cages was measured by releasing 24 males with 24 females vs. 24 males only per cage equipped with a single central monitoring trap. Mean cumulative catch was 10.7 ± 2.3 vs. 17.3 ± 0.6, respectively, whereas trap findability was 0.75 ± 0.03. Relative attractiveness of individual virgin females deployed in small screened cages as lures in traps caught 1.0 ± 0.2 male vs. 2.9 ± 0.6 by 0.1-mg codlemone lures, or 1:2.9, a ratio similar to the 1:3.3 reported for European leafroller moth (4). These efficiency and catch data were used to estimate female activity (female equivalent of D_a) by using Eq. **S5** and retention time using Eq. **S6**, respectively, but with the substitution of ♀ for D throughout. Resultant female activity was 0.04, whereas retention time was 0.08.

Section E: Supplementary Discussion

Where the sexual lifespan is ≈4 d, we postulate that D_a values of ≈0.25 will be common for codling moth mating-disruption formulations, as various commercial formulations release pheromone at dosages that will attract and inactivate for one diel cycle. For pests experiencing temporal superimpositions of hours-long physiological after-effects upon hours-long windows of sexual activity, we predict D_a values will be quantal above and continuous below ≈0.1. If deactivation longer than one diel cycle is not possible, D_a values will not exceed 0.25 for a pest with a sexual lifespan of 4 days. In such cases, attract-and-remove formulations will be superior, as they will yield D_a values of 1.0, if each visit removes that male permanently. However, under any form of mating disruption by competitive attraction, the efficacy return per additional dispenser deployed will always progressively diminish and only approach 100% disruption asymptotically (see sticky dispenser of Fig. 3*A* which also predicts the expected efficacy for an attract-and-remove formulation).

Section F: Generalized Competitive Attraction Equation and Suggestion of Its Application to Marketing

Eq. **S3** can be broadly generalized as Eq. **S7**, fitting any type of

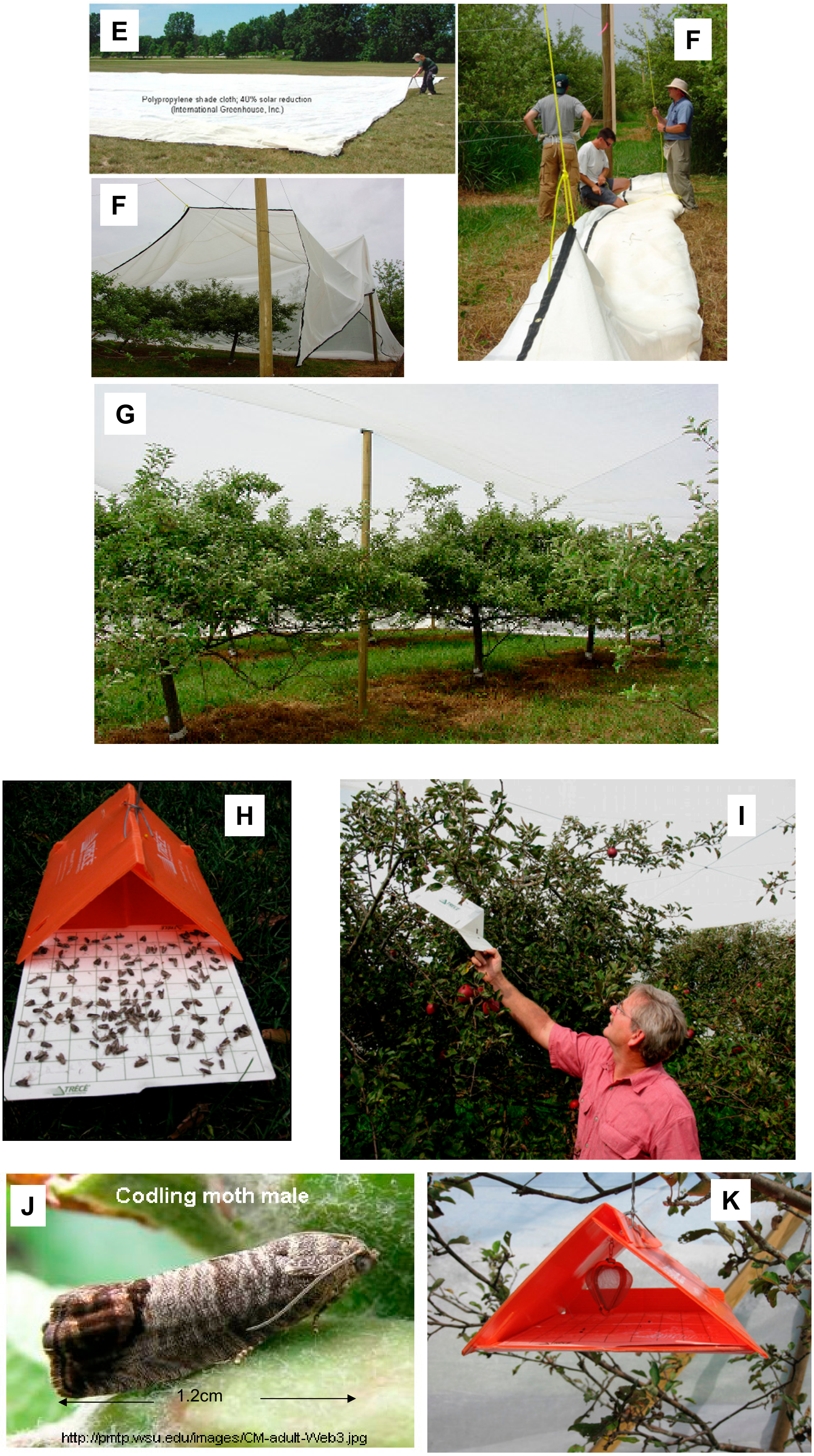
$$r = U_{\mathrm{den}} p_{\mathrm{RU}} p_{\mathrm{U}} RU_{\mathrm{L}} R_{\mathrm{den}} / (U_{\mathrm{den}} + p_{\mathrm{RC1}} p_{\mathrm{C1}} RC_{\mathrm{1L}} C_{\mathrm{1den}} + p_{\mathrm{RC2}} p_{\mathrm{C2}} RC_{\mathrm{2L}} C_{\mathrm{2den}} + p_{\mathrm{RCn}} p_{\mathrm{Cn}} RC_{\mathrm{nL}} C_{\mathrm{nden}}). \qquad \mathbf{[S7]}$$

competitive attraction where: r equals response of responders R to a unit U; p_{RU} equals probability R makes sensory contact with U; p_{U} equals probability U causes R to form an RU complex after sensing U; RU_{L} equals longevity of the RU complex; C_1, C_2, C_n equals competitors 1, 2, n, and probabilities of sensory contact with them are designated $p_{\mathrm{RC1}}, p_{\mathrm{RC2}}, p_{\mathrm{RCn}}$; their respective probabilities in forming a tight responder–competitor complex with the responder are $p_{\mathrm{C1}}, p_{\mathrm{C2}}, p_{\mathrm{Cn}}$; longevities of responder–competitor complexes are $\mathrm{RC}_{\mathrm{1L}}$, etc.; and subscript den equals density of respective agents interacting in a common arena following standard rules of probability. We anticipate that this or related forms of Eq. **7**, along with the associated graphical tools presented here for analyzing and interpreting theoretical and experimental data, will find important applications across and beyond biology. The extent to which telling information can be indirectly derived about competitors of U will be proportional to the depth of knowledge the analyst holds about properties of U.

As a marketing example of Eq. **S7**, let U and $C_1 - C_n$ equal competing products in a common marketplace; p_{RU} equals effectiveness of advertising U; p_{U} equals probability U is purchased, once a responder is aware of U, and RU_{L} equals interval between last and next purchase. Inventory needs in a particular location might be estimated by r, provided r_{den} were known.

1. Knipling EF (1979) *The Basic Principles of Insect Population Suppression and Management.* (USA Sci Educ Admin) USDA Agric Handbook 512.
2. Miller JR, Gut LJ, de Lame FM, Stelinski LL (2006) Differentiation of competitive vs. non-competitive mechanisms mediating disruption of moth sexual communication by point sources of sex pheromone (Part 1): Theory. *J Chem Ecol* 32: 2089–2114.
3. Miller JR, Gut LJ, de Lame FM, Stelinski LL (2006) Differentiation of competitive vs. non-competitive mechanisms mediating disruption of moth sexual communication by point sources of sex pheromone (Part 2): Case studies. *J Chem Ecol* 32:2115–2143.
4. Deland JP, Judd GJR, Roitberg BD (1994) Disruption of pheromone communication in three sympatric leafroller (Lepidoptera: Tortricidae) pests of apple in British Columbia. *Environ Entomol* 23:1084–1090.

Fig. S1. (*A*) Aerial photograph of the 20 large field cages; note size of automobile towing trailer on interstate highway. (*B*) Individual cage measuring 19 × 19 × 3.5 m and covering 12 apple trees. (*C*) Gripple apparatus for tightening trellis wires. (*D*) Elements of cage superstructure: posts, braces, trellis wire. (*E*) Shade cloth used as netting for a single cage laid out for preinstallation folding. (*F*) Net installation. (*G*) Half of the interior of one cage. (*H*) Monitoring trap showing high catch of codling moth males on the sticky liner covering trap bottom. (*I*) J.R.M. checking trap. (*J*) Codling moth male. (*K*) Cages used to deploy individual females in traps.



http://pmtp.wsu.edu/images/CM-adult-Web3.jpg

Fig. S1. continued.